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HEAVY-DUTY DIESEL VEHICLE INSPECTION AND MAINTENANCE STUDY

FINAL REPORT
VOLUME III

DEVELOPMENT AND VALIDATION OF I/M TEST PROCEDURES

Submitted to:

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1.0 INTRODUCTION

In order to protect and improve the quality of its air, the State of California is interested in minimizing pollutant emissions from heavy-duty diesel trucks and buses. Diesel-engined vehicles are major contributors to ambient levels of particulate matter and oxides of nitrogen (NOx) in urban air. Diesels also emit lesser (but still significant) amounts of unburned hydrocarbons (HC), and a small amount of carbon monoxide (CO). Diesel HC emissions are of special concern, since the hydrocarbon species emitted include polynuclear aromatic compounds, nitro-aromatics, and other toxic, carcinogenic, or mutagenic species. Diesel HC and aldehyde emissions are also responsible for the characteristic diesel odor.

New motor vehicles must meet strict pollutant emission standards before they can be sold. In order to improve the level of emissions control in customer use, however, California and many other states have found it necessary to implement programs of periodic inspection and maintenance (I/M) to check emissions levels and/or the functioning of emissions controls and require corrective repairs where necessary. California presently has a strong I/M program for light-duty and some heavy-duty gasoline vehicles, and has considered a similar program for light-duty diesels. Heavy-duty vehicles, especially diesels, have traditionally been exempted from I/M requirements, however.

Implementation of I/M programs for diesels has been impeded by the technical difficulty of developing a suitable emissions test, and by uncertainty as to the magnitude of the problem and of the cost-effectiveness of an I/M program. In response to the need for improved control of heavy-duty diesel emissions, however, the California Air Resources Board (ARB) commissioned Radian Corporation to quantify the problem of excess emissions from heavy-duty diesel trucks and buses, to develop preliminary I/M procedures for these vehicles, and to estimate the costs and cost-effectiveness of implementing an I/M program for heavy-duty diesels.

1.1 Outline of the Study

The project was divided into five major tasks, as listed below.

(1) Quantify the problem of excess emissions from heavy-duty diesels due to poor maintenance and/or tampering with emission controls. This task included defining common emissions-related defects, estimating the frequency of defects in the truck population, estimating the emissions consequences of each defect, and combining these estimates with data on truck populations and travel patterns to estimate the impact of excess emissions from heavy-duty diesels on air quality and public offense due to excessive smoke.

(2) Develop and document a periodic inspection procedure and a quick roadside smoke opacity check to identify heavy-duty diesel vehicles having excessive emissions. The periodic inspection procedure was intended to be conceptually similar to the procedures for the present Smog Check Program for light-duty gasoline vehicles. The roadside opacity check procedure was intended as a quick and simple check for excessive emissions which could be applied at a truck weigh station or similar environment.

(3) Estimate the costs and emissions benefits of implementing the procedures developed in Task Two, assuming that the emissions defects identified by the procedure are properly repaired.

(4) Validate the procedures developed in Task Two by applying them to a representative sample of trucks in a blind test.

(5) Prepare a final report documenting the work.

1.2 Outline of the Report

The final report for this project has been divided into four volumes, of which this is Volume III. The volume numbers and their titles are as follows:

I. SUMMARY REPORT

II. QUANTIFYING THE PROBLEM

III. DEVELOPMENT AND VALIDATION OF I/M TEST PROCEDURES

IV. I/M PROGRAM DESIGN AND COST-EFFECTIVENESS ANALYSIS

Volume I presents an overview of the other three volumes, and summarizes the major conclusions and recommendations. Volume II describes a computer model of heavy-duty diesel emissions developed for this project, and presents the model results for the case with no I/M program. Volume III, this volume, describes the development and validation of emissions test procedures to identify heavy-duty diesel vehicles which are excess emitters. Volume IV, finally, outlines several possible designs for I/M programs using these procedures, and estimates the emissions reductions and cost-effectiveness for each.

1.3 Guide to the Remainder of Volume III

This report is divided into seven sections, of which this Introduction is the first. Section Two, following, describes the candidate test procedures for the Periodic I/M Test (PIMT) and Roadside Opacity Check (ROC) developed under Task Two, and discusses the considerations that entered into their development. Sections Three and Four describe the tests carried out to validate of these procedures. Fifty-two trucks were given screening tests using the ROC. Section Three describes these tests, and presents the results.

These were used to select eleven trucks for testing at ARB's Haagen-Smit Laboratory. The laboratory tests included both the Periodic I/M Test Procedure and gaseous and particulate emission measurements. Six of the higher-emitting trucks were then diagnosed, repaired, and given post-repair emissions tests. The repair results are also discussed in Section Four.

The data generated by this test program are analyzed in Section Five. This section addresses the key issue of whether the proposed I/M test procedures are valid and useful for detecting high-emitting vehicles, and defines those elements of the test procedure which are most effective in doing so. Other issues addressed in this section include the correspondence between opacimeter readings and visual estimates of smoke opacity, and the correlations between HC and NO_x concentrations in specific modes with composite emissions of these pollutants. Section Six describes a database of heavy-duty diesel emissions tests performed by the New York City Department of Environmental Conservation (NYCDEP), and presents our analysis of these data. Section Seven, finally, presents our conclusions and recommendations for the ROC and PIMT procedures, based on the foregoing analyses.

1.4 Limitations and Caveats

The test procedures described in this report were developed as prototypes of test procedures to be used in a full-scale heavy-duty diesel I/M program. Our limited vehicle testing and our analysis of the available data indicate that these prototype procedures are practical, and effective in identifying heavy-duty diesel vehicles with excessive emissions. However, they are prototypes only--much work remains to be done to refine the test equipment and procedures, define appropriate cutpoints, and to evaluate the correlation between the test results and actual pollutant emissions for a larger sample. It is important to recognize the limited nature and scale of the validation possible in this initial project. The reader is also cautioned that many details of test procedures and equipment require refinement before a large-scale heavy-duty diesel I/M program will be practical.

2.0 DEVELOPMENT OF CANDIDATE I/M TEST PROCEDURES

Radian's objective in Task Two was to develop two inspection test procedures for heavy-duty diesel vehicles: a Periodic Inspection and Maintenance Test (PIMT) procedure and a Roadside Opacity Check (ROC). The purpose of each of these procedures is to identify heavy-duty diesel vehicles which are producing excessive pollutant emissions, in order to require that the problems causing these excessive emissions be repaired. The ROC is intended to be used for random enforcement testing. For this reason, it was required that it be performable within the physical confines of a California Highway Patrol weigh station. The PIMT, as its name implies, is intended to be used in a periodic (e.g. annual or biennial) inspection program, analogous to the existing Smog Check Program for light-duty vehicles.

Due to the public offense from excessive diesel smoke, many jurisdictions have established smoke emissions regulations, enforced by a variety of tests. Most of these have relied on visual estimates of smoke opacity, using the Ringelmann scale or some analogous measure. The Ringelmann scale has been shown to be generally unreliable for this purpose (EMA, 1983). As discussed in Section 5.1, however, visual estimates assisted by a transparent smoke opacity guide are sufficiently accurate to be used for screening purposes.

Portable smoke opacity meters (opacimeters) which can be attached to the end of the stack have come into fairly widespread use. Jasper and coworkers (1983) developed several short tests for smoke opacity in buses, and applied these to the Portland, Oregon bus fleet. A similar study by ARB (Shears, 1986) tested many of the same techniques on vehicles from the Southern California Rapid Transit District (SCRTD) bus fleet, with generally favorable results. Opacimeters have also been used for inspection and maintenance of diesel buses in New York and New Jersey. Nearly all of these programs have been aimed primarily at the control of visible smoke, rather than particulate or gaseous emissions--although these might be reduced as a side effect.

The objective of this project was to develop I/M procedures to reduce gaseous (HC and NO_x) and particulate emissions, as well as visible smoke, by identifying engines with specific types of problems which result in excess emissions. Many candidate test procedures were considered. Most of these procedures appeared to be suitable for detecting one or more types of emissions-related defects, but no single procedure appeared capable of detecting all common defects in diesel engines. As a result, the test procedures proposed for the validation testing included a number of candidate procedures. Due to uncertainty over the relative effectiveness of different tests, the candidate test procedures included more individual tests--and were thus somewhat more elaborate--than was considered desirable for the final procedures. It was intended that the results of the validation testing in Task Four be used to identify those specific tests among the ones specified for the candidate procedures which were most effective in identifying high-emitting vehicles.

Before beginning the validation testing, the original candidate procedures were tried out on two trucks loaned for this purpose by the County of Los Angeles. These initial tests resulted in some modifications to increase the practicability of the procedures. The following subsections describe each of the two candidate test procedures as they were modified as a result of these trial runs. It should be noted that not all of these procedures were found acceptable in the validation testing, and that only a few are being recommended for implementation in the PIMT or ROC.

2.1 Roadside Smoke Opacity Check

Candidate procedures for the roadside smoke opacity check were limited to those which can reasonably be performed at a truck weigh station or other roadside environment, and were thus limited to off-dynamometer, noninvasive procedures. Four candidate procedures were proposed: a quick acceleration in gear; lug-down in gear (manual transmission vehicles only); stall idle (automatic transmission vehicles only); and snap idle. All of these except the lug-down had previously been tested by Shears and coworkers (1986) on SCRTD transit buses.

Smoke opacity in any of these tests could be judged either with an opacimeter on the stack or by a trained observer. The accuracy of visual observation vs. the opacimeter measurements is discussed in Section 5.1. For mass testing, the most efficient approach would be to make a "first cut" by visual observation, with subsequent opacimeter testing in marginal cases.

2.1.1 Full-Power Acceleration

The validation testing showed that the acceleration peak opacity was the most effective criterion for detecting high emitters, and it is being recommended for the final ROC.

Procedure--Choose a gear such that the vehicle speed will be 10-20 MPH at governor speed, or the lowest gear available if no gear gives a 10-20 MPH speed. Beginning with a fully warmed-up engine at idle and the vehicle stopped, accelerate rapidly to governor speed (i.e. push the accelerator to the floor and hold it there). If governor speed is greater than 20 MPH, accelerate only to 20 MPH. Record the initial peak in smoke opacity and the steady-state value after the engine reaches governor speed (this requires the use of a strip-chart or other recorder with the opacimeter).

Tentative cutpoints proposed for the screening test were 35% (or 5% over the Federal "peak" certification, whichever was higher) for the peak and 6% for the steady-state opacity.

Discussion--The work of Shears and coworkers (1986) indicates that peak smoke opacity on rapid acceleration is a good indicator of tampering with the puff limiter, turbocharger problems, other air system problems, and injector problems. High steady-state smoke usually indicates injector problems, or air-system problems such as a dirty air filter. This work was limited to transit buses using Detroit Diesel Allison (DDA) engines, but similar results were observed on other engines in the validation testing.

The peak opacity cutpoint was based on a review of Federal smoke certification data, which shows that most "C" (peak) smoke values are under 30% (note that engines which were certified over 30% would have a proportionately higher cutpoint). Transit bus engines appear to be capable of meeting a much lower peak opacity standard--in the neighborhood of 15% opacity (Crawford et al., 1984). The 6% steady state value was based on engineering judgement. However, the steady-state opacity was not found very useful in detecting high emitters, and was dropped from the recommended procedure.

In comments on a earlier draft of this report, the Engine Manufacturer's Association strongly criticized the proposed "peak" cutpoint of 35% opacity (or 5% over the Federal "peak" certification value, if that is higher) and argued for a cutpoint of 60%. In our opinion, the EMA cutpoint is too high, but a cutpoint of 50% opacity might be justified. Based on the results of our visual smoke survey, as many as 50% of trucks now in use could be expected to fail this test at 35% opacity. Increasing the cutoff point to 50% opacity would decrease the expected failure rate to about 25%, while increasing it to 60% opacity would reduce the failure rate to about 6.5%. In addition, it would be relatively easy to make even a high-emitting truck pass the I/M test at 60% opacity by adjusting the smoke limiter.

Part of the reason for this controversy is the fact that the peak opacity alone is not a complete measure of smokiness on acceleration. The <u>width</u> of the peak is as important as its height in assessing acceleration smoke. For this reason, some measure of the average smoke opacity over the acceleration (such as the Federal "A" smoke measurement) might be more useful than the peak for I/M purposes. Obtaining such a measure would require more sophistication in the opacimeter electronics, but would present no serious problems. This question is recommended for further investigation in subsequent programs.

2.1.2 Lug-Down Against the Service Brake

Procedure--This procedure is applicable to vehicles with manual transmissions (or automatics using a solid clutch linkage). It can be run as a continuation of the acceleration test above, or as a separate test if the acceleration test is not being used. Choose a gear such that the vehicle speed will be 10-20 MPH at governor speed, or the lowest gear available if no gear gives a 10-20 MPH speed. Determine in advance the vehicle speed corresponding to 60% of governor speed or the maximum-torque speed, whichever is higher. Beginning with a warmed-up engine, accelerate to governor speed in gear (or 20 MPH, whichever is lower). Holding the accelerator pedal all the way down, smoothly apply the service brake in order to slow the vehicle down to the predetermined 60%/max torque speed over a period of 4-6 seconds. DO NOT run the engine at full power against the brakes for more than 6 seconds.

After reaching the predetermined speed, smoothly release both the brake and the accelerator to avoid stalling the engine or having the vehicle jerk forward. Record the highest smoke opacity over the lug-down, ignoring the possible sharp peak as the brake and accelerator are released (this will require a strip-chart or other recorder with the opacimeter). The tentative cutpoint proposed for the screening test was 20% opacity or 5% over the Federal "lug" certification, whichever was higher.

Discussion--When performed on a dynamometer, the lug-down test is a good indicator of air-system problems, injector problems, and maximum fuel set too high. Since air and injector problems were estimated to account for most excess emissions from diesels, this was considered an especially useful test. It proved difficult to perform reproducibly, however, and raised significant safety concerns. For these reasons, its use is not recommended. A similar test--optionally involving the use of rollers under the truck's drive wheels so that it can be performed standing still--has recently been proposed as an international standard (ISO, 1986).

The proposed cutpoint for this test was based on the Federal "B" smoke standard. This is presently set at 15% opacity, but was higher in previous years. Based on the visual smoke survey results, this would be expected to give a failure rate of around 15-25% if the test could be performed reproducibly.

2.1.3 Stall Idle

This procedure's name is misleading, since the engine does not idle but operates at near-maximum torque. This name has been used in previous reports, however, and is retained here for clarity.

Procedure--This procedure applies to automatic-transmission vehicles with hydraulic torque converters. Begin with a warmed-up engine and the vehicle idling in gear. Apply the brakes firmly to prevent the vehicle from moving, then suddenly depress the accelerator pedal as far as possible. The engine should rapidly accelerate to the torque converter stall speed. Allow it to run at this speed for one or two seconds before releasing the accelerator and returning to idle. However, DO NOT run with full power against the torque converter for more than 6 seconds under any circumstances. If the engine hasn't reached a stable speed in 6 seconds, release the accelerator anyway.

Record the peak opacity during the acceleration and the steady-state opacity after reaching governor speed (this will require a strip-chart or other recorder with the opacimeter). Tentative cutpoints proposed for the screening test were 35% or 5% over the Federal "peak" certification for peak opacity, and 10% for the steady state opacity.

Discussion--Shears and coworkers (1986) found that the stall idle test is the most effective stationary test for most emission-related defects in transit buses. The peak smoke opacity is diagnostic for puff-limiter maladjustment, high maximum fuel rate, and injector problems. The steady-state opacity is diagnostic for injector problems, air-system problems, and (to a limited extent) retarded timing. The results of this test are similar to those of the acceleration test, and it is recommended as an alternative to the acceleration test for vehicles with automatic transmissions.

The peak cutpoint for this procedure was based on the same considerations as the acceleration procedure. The steady-state cutpoint is higher, however, reflecting the fact that the engine is heavily loaded in the steady-state mode of this procedure. (Note that the steady-state criterion is not included in the final recommendations, however). The failure rates for this test are expected to be about the same as for the acceleration test.

2.1.4 Snap Idle

Procedure--Begin with the engine warmed up and idling in neutral. With the transmission still in neutral, suddenly depress the accelerator pedal as far as possible. The engine should rapidly accelerate to governor speed. Hold it at governor speed for a few seconds, then smoothly release the accelerator to let it return to idle. Record the peak opacity and the steady-state opacity at governor speed (this requires a strip-chart or other recorder for the opacimeter). Tentative cutpoints proposed for the screening survey were 40% (or 10% over the Federal "peak" certification value) for peak, and 6% for steady-state.

Discussion--The major advantage of the snap idle test is its simplicity and the fact that it can be done with the vehicle standing still. Its major diagnostic utility is for misset puff limiters and bad injectors; it does not appear to show up air system problems well. This test appears to give higher peak smoke readings than the acceleration test, thus the higher cutpoint. It was also found that the correlation between acceleration smoke and snap idle smoke is engine-dependent. In the validation test, some engines showed snap-idle peak opacities exceeding 80%, but low or moderate acceleration peaks. Because of this, this test is not recommended for general use.

2.2 Periodic I/M Test Procedure

The candidate procedures for the Periodic I/M Test (PIMT) were designed to be performed in a diesel repair shop or similar facility. These procedures included visual and functional checks of emissions control equipment; smoke opacity measurements under acceleration, lug-down, and road-load conditions; and HC and NO_x concentration measurements in specific modes. Not all of these procedures are being recommended for inclusion in the final PIMT.

In developing these procedures, the question of whether to base them on a chassis dynamometer or not had to be addressed. Chassis dynamometers capable of handling a heavy-duty truck typically cost $100,000 to $200,000 installed, and not all truck repair stations have them. Thus, a decision to rely on dynamometers would exclude many diesel repair shops from performing I/M tests. On the other hand, the need to test for excessive smoke and NO_x emissions under load, and the greater controllability and repeatability of dynamometer loading compared to alternative means argued for a dynamometer-based procedure.

In order to determine the number of heavy-duty chassis dynamometers in use, Radian contacted each of the major dynamometer manufacturers by telephone. The results of this survey are shown in Table 2-1. According to the manufacturers, at least 200 heavy-duty chassis dynamometers are in use in California (including those in fleet operations). In addition, Caterpillar--a major manufacturer of truck engines--recently developed routine diagnostic procedures which require a specific model of heavy-duty chassis dynamometer, and has required that all authorized Caterpillar service facilities have one of this model available.

There are approximately 200,000 heavy-duty diesel vehicles registered in California (Horie and Rapoport, 1985), or about 1,000 for each existing dynamometer. For comparison, there are about 1,600 light-duty cars and trucks subject to the Smog Check for each licensed Smog Check station

TABLE 2-1. HEAVY-DUTY CHASSIS DYNAMOMETERS IN USE IN CALIFORNIA

Manufacturer	Total Dynamometers	Private	Public	Roller Size
Clayton	140[a]	85	55	4-24"
Go Power	5[b]	2	3	6-24"
Maxwell	20-25[c]	12-17	8	---
Superflow	15[d]	13	2	1-36"
Taylor	28[e]	28	-	4-12.5" 4-20" 6-20" 8-20" 4-35.4"
TOTALS	208-213	140-145	68	

a Per personal communication with Don Dabbert, Product Manager for Clayton Dynamometers, on March 12, 1986.

b Per personal communication with Dan Roberts, Western Regional Sales Manager for Go Power Corporation, on February 10, 1986.

c Per personal communication with Lloyd Maxwell Jr., V.P. of Marketing for Maxwell Dynamometers, on February 11, 1986.

d Per personal communication with Dick Kenngott, Superflow Representative for Superflow Dynamometers, on February 3, 1986, February 11, 1986 and March 12, 1986 and personal correspondence on February 17, 1986.

e Per personal communication with William Flamme, West Coast Factory Representative for Taylor Dynamometers and Machine Co., on February 11, 1986 and personal correspondence of February 19, 1986.

(BAR, 1986)--and many Smog Check stations are significantly underused. Thus, it appears that adequate dynamometer capacity to support a heavy-duty diesel I/M program would be available. While we recognize that not all of the existing dynamometers would necessarily be available for use in an I/M program, the large number of dynamometers in use is a strong indicator that more could be built rapidly if they were required.

Based on the foregoing, it was decided to develop test procedures based on the use of a chassis dynamometer. In addition, we assumed that something analogous to the automatic Test Analyzer System (TAS) used in the Smog Check Program would be required. In addition to logic and recording capabilities, this system was assumed to be capable of measuring exhaust smoke opacity, CO_2, and (optionally) HC and NO_x concentrations. Preliminary inquiries with several instrumentation suppliers indicated that such a system would be well within the present state of the art, and that it could probably be sold at a price comparable to the more expensive of the TAS analyzers used in the current Smog Check Program. Detailed specification or development of such a system was beyond the scope of the present work, however, and was not attempted.

2.2.1 Visual/Functional Inspections

These inspections were proposed as a possible alternative to emissions measurements, especially for NO_x, and as a deterrent to tampering. Some of the inspection procedures listed (e.g. of injection timing) would be quite time-consuming and intrusive, and are not recommended, since NO_x measurements appear to be a feasible and more suitable approach.

Procedure--Visually inspect the air intake and exhaust system for evidence of pressure leaks (in turbocharged systems), or excessive intake or exhaust restriction (caused, e.g. by a dirty air filter, corroded muffler, or collapsed hose). If feasible, check the aftercooler for clogging or fouling of the heat transfer surface. Inspect the seals and tag wires on the fuel injection pump for tampering, and examine the puff limiter for signs of tampering or malfunction. Inspect the injection pump, fuel lines, injectors, and filters for leaks.

If applicable, perform a functional check of the EGR valve.

If applicable, check that seals or other tamperproofing on the electronic control system are intact. Check that no trouble lights are on, and interrogate the electronic control system for trouble codes. If applicable, check that the trap-oxidizer system is present, and check for possible tampering (with special attention to any bypass valves).

Check for evidence of tampering with the injection timing (index marks lined up properly, etc.) Optionally, perform a functional check of injection timing on injection systems using high-pressure injection lines (i.e. all engines except DDA and Cummins), using a pressure-pulse sensor on the injection line. Check DDA engine timing by removing the rocker arm covers and measuring injector clearance with an appropriate gage. (Note-direct measurements of injection timing are no longer recommended, since measurement of NO_x concentration in the exhaust provides a simpler check).

Discussion--Inspection of the emission control systems is expected to be a powerful deterrent to tampering. Tampering with trap-oxidizers and EGR systems should be readily detectable. Tampering with electronic controls and with most designs of fuel pumps should also be detectable by inspecting the seals placed on these adjustments by the fuel injection shop. This would require regulations to define breaking those seals as "tampering", however.

2.2.2 Dynamometer Acceleration Opacity

Procedure--Begin with the engine warmed up and idling in neutral. Select the gear that the vehicle would normally start in with a light load. Determine the dynamometer speed corresponding to rated engine speed in that gear, and preset the power absorption unit to absorb 50% of rated power at this speed. Smoothly depress the accelerator while letting in the clutch so as to transmit full power to the wheels as quickly as possible, then allow the vehicle to run up to governor speed with the accelerator fully depressed. Record the peak smoke opacity and the steady-state opacity at governor speed. Tentative cutpoints proposed for the validation testing were 35% (or 5% over the Federal "peak" certification) for peak opacity and 6% for steady-state opacity. Based on the visual smoke survey, this peak cutpoint would result in a failure rate of about 50%.

Discussion--This procedure is essentially a dynamometer version of the stall idle, one which is applicable to both manual and automatic transmissions. As such, it should be effective in detecting misset smoke limiters, problems with turbocharger dynamic response, bad injectors, and air system problems such as dirty air filters. It was found to be very effective in detecting high-emitting trucks in the validation testing. As discussed above, a cutpoint based on the average acceleration smoke opacity rather than the peak might be more appropriate. This question is recommended for further research.

2.2.3 Dynamometer Lug-Down Opacity

Procedure--Choose a gear which will allow speeds of 40-55 MPH at governor speed. Determine in advance the "intermediate speed" (60% of rated speed or the maximum-torque speed, whichever is greater) for the engine, and the corresponding vehicle speed. Determine also the speeds corresponding to 100%, 90%, 80%, and 70% of rated speed. With a warmed-up engine, accelerate under minimal dynamometer load to full governor speed. With the accelerator pedal fully depressed, gradually load the dynamometer until engine RPM drops to rated speed. Record the opacity and measured power output. With the accelerator pedal still fully depressed, increase the dynamometer loading to reduce the engine speed in turn to 90%, 80%, and 70% of rated speed, and then to the predetermined "intermediate speed". Record the smoke opacity and power output at each speed. Tentative cutpoints proposed for the validation testing were 20% opacity (or 5% over the Federal "lug" certification) at any point.

Discussion--The lug-down procedure is commonly used as a diagnostic tool, and the opacity results were found to correlate fairly well with steady-state emissions in the validation test. In addition to engine power problems, it is also excellent at detecting injection and air system problems and too-high maximum fuel settings. Too low a maximum fuel setting (indicated by low power output) would also be suspicious, as the fuel might have been "turned down" to get a marginal set of injectors past the smoke test.

The proposed cutpoint for this test was based on the Federal "B" smoke standard. This is presently set at 15% opacity, but was higher in previous years. The validation test results indicate that this cutpoint may be somewhat too high (see Figure 5-13), and that 15% opacity might be more appropriate. Based on the visual smoke survey results, the 20% opacity criterion would be expected to give a failure rate of around 15-25%, while lowering the cutpoint to 15% opacity would produce a failure rate of about 35-40%.

2.2.4 Dynamometer Road-Load Opacity

Procedure--Depending on the dynamometer control setup, this procedure may be advantageously combined with the lug-down test, or it can be run after the lug-down is completed. For each of the test points in the lug-down test except for the "intermediate speed", calculate 75% of the measured power output at full throttle. Adjust the dynamometer speed and load to reproduce this power output at the given speed. Measure and record the smoke opacity. The tentative cutpoint defined for the screening tests was 5% opacity at any point.

Discussion--This procedure was intended to identify problems--such as retarded timing or fouled injectors--which can cause high particulate emissions over the entire range of engine operating conditions. It will also identify problems which have been "masked" by turning down the maximum fuel rate to reduce full-power smoke. Many diesel engines smoke a little at full power, since the fueling rate is often smoke-limited (especially for naturally-aspirated engines). Smoke density falls off rapidly with decreasing load, however, so that at 75% load there should be essentially no smoke. Any significant opacity in these operating modes indicates a significant emissions problem.

The tentative cutpoint for this test was chosen based on a "no visible smoke" criterion. The validation test results and NYCDEP data suggest that this value may be too high, however. The validation test results also showed an increase in opacity near the maximum torque speed. For best consistency, this value should be measured at no less than 70% of rated speed. Based on the results of the visual smoke survey, a 5% opacity criterion should result in a failure rate of at least 25%.

2.2.5 Dynamic Injection Timing

This procedure was proposed to check timing on engines in which the injection timing varies as a function of speed and/or load, and to deter tampering with variable timing devices. Since this can be done more effectively via NO_x measurements, this procedure is no longer recommended.

Procedure--Using a diesel engine timing sensor, measure the fuel injection timing along the lug-down curve and at idle, and compare these with the manufacturer's specifications. Tentative cutpoint: 2 degrees advanced or retarded from spec at any point.

Discussion--This procedure is intended to identify malfunctions or tampering in mechanical timing advances or electronic control systems which could lead to excessive NO_x or particulate emissions.

2.2.6 Exhaust NOx Concentration

Procedure--Measure exhaust-gas NO_x concentration in specific operating modes using a chemiluminescent or other appropriate NO_x analyzer. Compare the measured value with the tabulated data on NO_x concentrations taken from the certification process. The tentative cutpoint proposed for the validation testing was equivalent to 1 g/BHP-hr over the manufacturer's spec. Too low a NO_x value may also indicate overly retarded injection timing.

Discussion--This measurement is intended to serve as an indicator of injection timing, and especially of potential tampering therewith. It would also show up any aftercooler or EGR problems causing excessive NO_x. It has advantages over the timing measurement from a public-relations standpoint, since it directly measures pollutant output. Due to the NO_x/particulate trade-off, some such measure of NO_x output is desirable to discourage tampering aimed at passing the opacity test.

2.2.7 Exhaust HC Concentration

Procedure--Measure the HC concentration in the exhaust in specific operating modes, using a Flame Ionization Detector or other appropriate instrument. Compare with tabulated data on normal concentrations from the certification process. Tentative cutpoint: 50% over normal in either mode.

Discussion--Some types of injection system problems can cause excessive HC emissions without producing a lot of visible smoke. This technique is intended to detect such problems.

3.0 SCREENING TESTS USING THE ROADSIDE OPACITY CHECK PROCEDURE

Validation testing of the Roadside Opacity Check (ROC) and Periodic I/M Test (PIMT) procedures was accomplished in two stages. In the first stage, Radian and ARB staff applied the proposed ROC to 52 heavy-duty diesel trucks belonging to various government agencies, one private utility, and a commercial used-truck dealership. Based on the screening results, eleven of these trucks were brought into ARB's Haagen-Smit laboratory for additional testing, including both the PIMT procedure and gaseous and particulate emissions measurements. The screening tests and vehicle selection based on them are described in this section. The next section, Section Four, describes the laboratory testing procedures.

3.1 Test Procedure

Table 3-1 lists basic identifying and technical data for the 52 trucks tested during the screening process. Trucks were made available for testing by the Cities of Pasadena and Los Angeles, the U.S. Postal Service, State of California Department of Transportation, Southern California Edison, and by Los Angeles GMC-Freightliner Trucks, a commercial truck dealership. Except for those from L.A. GMC, all of the trucks tested were fleet trucks or truck-tractors in active service with their respective owners. The trucks tested at L.A. GMC were truck-tractors which had been traded in or consigned by their owners and were available for sale as used trucks.

One truck (SCE-005) was equipped with dual exhausts, each fed from one bank of a V-8 engine. Two sets of opacity measurements are reported for this truck, one from each bank.

The fleet trucks were made available for testing at a fleet maintenance yard, and were provided with drivers by the fleet owner. In all but one of these cases (that of the U.S. Postal Service), the fleet yard had sufficient clear space for the acceleration and lug-down tests. The U.S.P.S. trucks were

TABLE 3-1. TECHNICAL AND IDENTIFYING DATA FOR TRUCKS SCREENED

Unit Number	Truck ID Number	Engine			Trans.	Aspiration*	Mileage	Comments/Defects
		Make	Model	Year				
Pasadena-01	E442235	CAT	3208		Auto	NA	16516	No Known Defects
Pasadena-02**	E442248	CAT	3208	1982	Auto	TC		Overheating
Pasadena-03	E758236	DDA	6V71	1977	Auto	NA	44699	No Known Defects
Pasadena-04	E476575	CAT	3208T	1985	Auto	TC	3481	No Known Defects
Pasadena-05	E442238	CAT	3208	1983	Auto	NA	19875	Has EGR
Pasadena-06	E777618	CAT	3208	1981	Auto	NA	53054	No Known Defects
Pasadena-07	E757127	DDA	6V71	1980	Auto	NA	33403	Smoky
Pasadena-08**	E79880	DDA	8.2L	1982	Auto	NA	16604	No Known Defects
Pasadena-09	E442223	CAT	3208	1983	Auto	NA	10830	No Known Defects
Pasadena-10	E476628	GMC	8.2L	1986	Auto	TC	2800	No Known Defects
LA USPS-01	4600361	MACK	300 HP	1984	Manual	TC/A-A AC	39736	No Known Defects
LA USPS-02	4600363	MACK	300 HP	1984	Manual	TC/A-A AC	71041	No Known Defects
LA USPS-03**	1600574	CUMMINS	NTC 300CA	1981	Manual	TC/JWAC	154379	No Known Defects
LA USPS-04	1600565	CUMMINS	NTC 300CA	1983	Manual	TC/JWAC	168579	No Known Defects
LA USPS-05**	4600358	MACK	300 HP	1984	Manual	TC/A-A AC	52527	No Known Defects
LA USPS-06	3690329	DDA	8.2L	1983	Auto	TC	6611	No Known Defects
LA USPS-07	4801278	IHC	6.2L	1984	Auto	NA	14269	No Known Defects
LA USPS-08	4801199	IHC	6.2L	1984	Auto	NA	25690	No Known Defects
LA USPS-09	4801569	IHC	6.2L	1984	Auto	NA	33935	No Known Defects
LA USPS-10	3690328	DDA	8.2L	1983	Auto	TC	128057	No Known Defects
LA DPW-01	23005	DDA	6V92TAC	1984	Manual	TC/JWAC	24782	No Known Defects
LA DPW-02**	34053	CUMMINS	350NTC	1982	Manual	TC/JWAC	33713	No Known Defects
LA DPW-03**	22257	DDA	6V92TAC	1980	Manual	TC/JWAC	100026	No Known Defects
LA DPW-04	22161	DDA	6V92TAC	1978	Manual	TC/JWAC	88591	No Known Defects
LA DPW-05	21157	DDA	6V92TAC	1978	Manual	TC/JWAC	116494	No Known Defects
LA DPW-06	22167	DDA	6V92TAC	1978	Manual	TC/JWAC	93852	Blue Smoke-Oil Burner
LA SAN-07	37273	CUMMINS	L10	1986	Auto	TC/JWAC	108	No Known Defects
LA SAN-08	28078	CUMMINS	350NTC	1980	Manual	TC/JWAC	15985	No Known Defects
LA SAN-09	37240	CUMMINS	L10	1985	Auto	TC/JWAC	10269	No Known Defects
SCE-01	9030	CUMMINS	350NTC	1983	Manual	TC/JWAC	126990	40 Ton Load

(Continued)

TABLE 3-1. (Continued)

Unit Number	Truck ID Number	Engine Make	Engine Model	Engine Year	Trans.	Aspiration*	Mileage	Comments/Defects
SCE-02**	9029	CUMMINS	350NTC	1980	Manual	TC/JWAC	157498	No Known Defects
SCE-03**	1689	CUMMINS	350NTC	1984	Manual	TC/JWAC	83305	No Known Defects
SCE-04	7203	CUMMINS	350NTC	1976	Manual	TC/JWAC	303360	Mismatched RR TirES
SCE-05	6964	DDA	8V53	1971	Manual	NA	400518	Dual Exhause (Left)
SCE-05	6964	DDA	8V53	1971	Manual	NA	400518	Dual Exhaust (Right)
SCE-06	2005	CUMMINS	350NTC	1986	Manual	TC/JWAC	1217	No Known Defects
SCE-07	1990	CAT	V6-36	1980	Manual	NA	96396	No Known Defects
CALTRANS-01	3001	CAT	3208		Auto	NA	24877	No Known Defects
CALTRANS-02	3007	CAT	3208		Auto	NA	25217	New Engine
CALTRANS-03**	2726	IH	DT466		Manual	TC	33247	Smoky
CALTRANS-04	3456	IH	DT466		Manual	TC	12494	No Known Defects
CALTRANS-05	3563	CAT	3208	1983	Auto	NA	27530	No Known Defects
CALTRANS-06	3471	IH	DT466	1985	Auto	TC	8792	No Known Defects
CALTRANS-07	3001	CAT	3208	1980	Auto	NA	28217	Burns Oil, Gets <2 MPG
LA GMC-01	1039	CUMMINS	235	1968	Manual	TC		No Puff Limiter
LA GMC-02	1030	CUMMINS	400NTC		Manual	TC	451619	No Known Defects
LA GMC-03**	1034	CUMMINS	335NTC	1976	Manual	TC	514882	Very Smoky
LA GMC-04	1046	CAT	3406	1975	Manual	TC	539747	No Known Defects
LA GMC-05	929	CAT	3406	1981	Manual	TC		Smoky
LA GMC-06	243	CAT	3408		Manual	TC		Smoky
LA GMC-07	1033	CUMMINS	290NT	1977	Manual	TC		No Known Defects
LA GMC-08**	1026	DDA	8V71T	1977	Manual	TC	100006	Very Smoky
LA GMC-09	777	CAT	1693	1973	Manual	TC		Leaky Brakes

* NA: Naturally aspirated.
TC: Turbocharged.
JWAC: Jacket water aftercooler.
AAAC: Air-to-air aftercooler.

** Selected for emissions testing at HSLD.

tested on a little-used side street near the U.S.P.S. facility. Testing of the L.A. GMC trucks was conducted on a paved driveway leading to the dealership's maintenance shops. L.A. GMC did not provide a driver for their trucks, so these trucks were driven during testing by a contract employee provided by Radian.

To conduct these tests, a team typically consisting of one Radian and one ARB staff member travelled to the facility. Each truck was first warmed up to normal operating temperature, then the engine was stopped and the truck was instrumented with a Wager model 2000 portable smoke opacity meter on the exhaust stack, connected to a portable strip chart recorder carried in the cab of the truck. Figures 3-1 and 3-2 show typical installations. Truck identifying and technical data were also obtained and recorded at this point. The zero on the meter was set and the span was checked with the truck engine off. With the Radian staff member riding in the cab, the engine was then started and the idle smoke opacity reading noted.

For trucks with automatic transmissions, the Radian staff member then started the strip-chart recorder and directed the driver to conduct two snap idles by placing the transmission in neutral and suddenly depressing the accelerator. The driver was instructed to hold the accelerator depressed until the engine stabilized at governor speed. This was followed by two stall idle tests, which were conducted identically to the snap idles except that the transmission was in drive rather than neutral. These were followed by two full-power accelerations from a stop to governor speed, or to the maximum safe speed permitted by the testing location. The strip-chart recorder was then turned off and the instrumentation was removed from the truck.

For manual transmission vehicles, the test procedure was changed to eliminate the stall idle, replacing it with a full-power lug-down against the vehicle's service brake. The transmission gear setting was chosen to give a maximum vehicle speed (with the engine at governor speed) of 15-30 MPH. Often, one or two trial accelerations were needed to choose the right gear. The

Figure 3-1. Smoke Opacity Meter Setup for Field Screening.

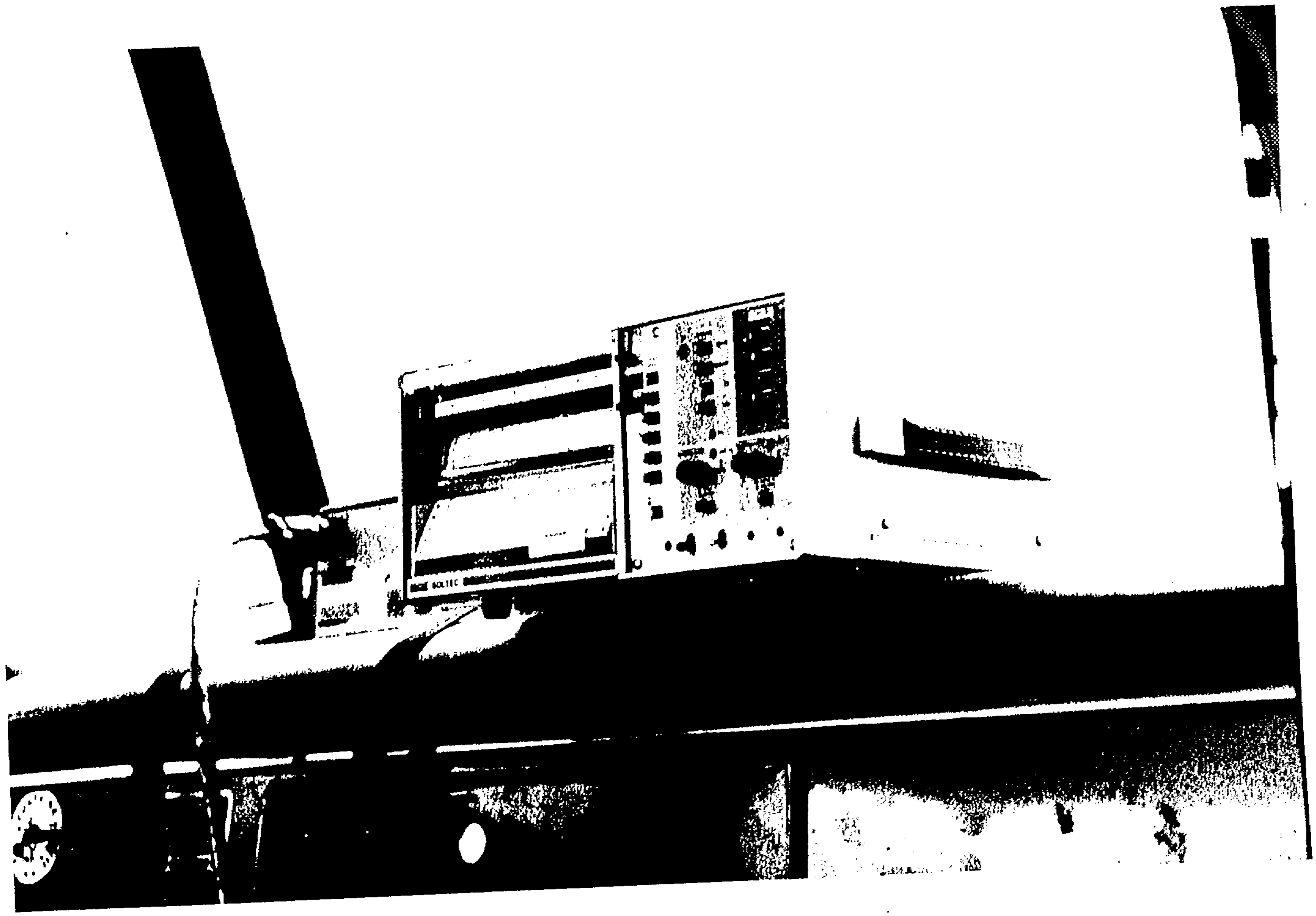


Figure 3-2. Smoke Opacity Recorder Setup for Field Screening.

driver was then instructed to accelerate as rapidly as possible from a stop to governor speed, without changing gears. Once at governor speed, he was instructed to press on the brake pedal with his left foot to bring the truck down to 60% of that speed, while simultaneously holding the accelerator pedal fully depressed with his right foot. Most drivers were uncomfortable with this procedure, and required several tries to obtain a good test. If feasible, two such acceleration/lug-down sequences were conducted back-to-back.

Continuous strip-chart recordings of the opacimeter output were used to determine the peak and stabilized opacity values for each test mode. These were taken immediately from the chart recorder trace and recorded on a data sheet for each truck. Figure 3-3 shows a typical opacity trace. In addition, a visual estimate of the peak and stabilized opacity in each mode was made by the ARB staff member, assisted by a photographic visual smoke scale provided by the Colorado Department of Health. These estimates were recorded separately on the data sheet. This was intended to provide data for a quantitative evaluation of the accuracy of visual smoke opacity estimation.

The total time required for a vehicle test was typically 10-20 minutes, although some vehicles took longer (especially at first). Most of this time was consumed by warming up and positioning the truck, and by the installation and removal of the opacimeter and strip-chart recorder. The actual testing typically consumed only 2-3 minutes, depending on the space available for the acceleration and lug-down tests. As testing proceeded, the team members became much more practiced at installing and removing the instrumentation, and acquired or fabricated various pieces of equipment to assist in the process. Based on this experience, we estimate that an experienced person could be expected to opacity check 4-5 trucks per hour on a routine basis, assuming that the trucks were available with the appropriate timing and that drivers were provided.

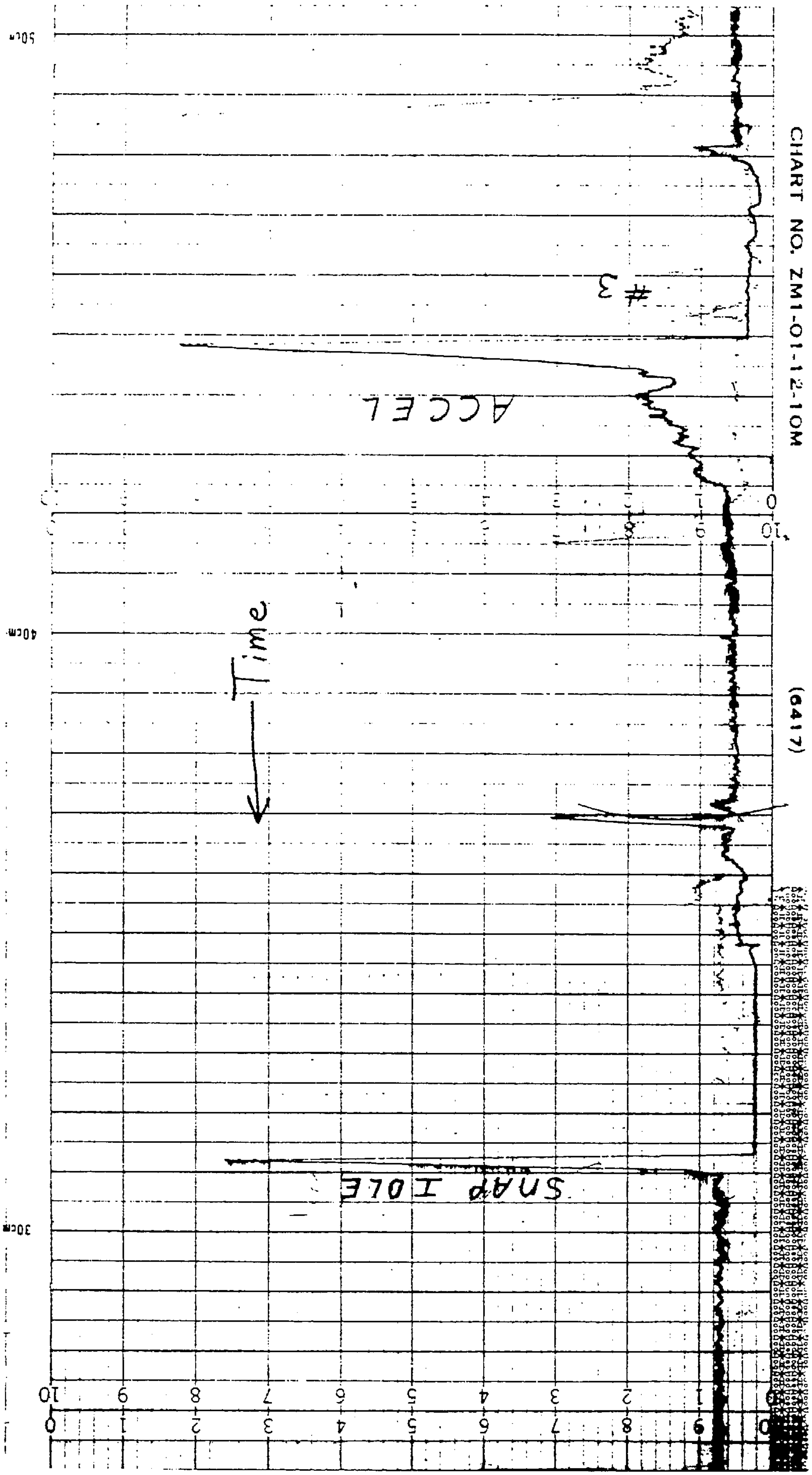


Figure 3-3. Typical Opacity Trace.

3.2 Screening Test Results

Table 3-2 lists the modal smoke opacity data for each truck in the survey, as measured with the opacimeter, while Table 3-3 gives the same information for the visual opacity estimates. Inspection of the two tables shows that the two opacity measures generally correspond fairly well, but with some notable exceptions. A statistical assessment of the correlation between these two measures is deferred to Section 5.1

Also shown in the two tables are the pass/fail determinations for each truck, comparing the measured or estimated opacity to the tentative failure criterion for each mode proposed in Task Two. If the measured opacity is less than or equal to the criterion, the truck would pass an I/M test based on that criterion. This is indicated by a "P" in the appropriate cell. Otherwise, the truck would fail, indicated by an "F".

Inspection of the pass/fail data in Tables 3-2 and 3-3 also shows a fair degree of correspondence, both between the visual and opacimeter measurements for a given mode, and between the different test modes. Generally, a truck which fails one test mode is likely to fail others as well, and often to a similar degree. Needless to say, the degree of correlation between modes is heavily affected by the specific failure criteria chosen. A full discussion of the correlation between modes and the appropriateness of the tentative failure criteria defined in Task Two is deferred until Section Five.

Figures 3-4 through 3-10 display the results of Table 3-2 in graphic form.

3.3 Problems with the Test Procedure

Aside from the usual problems of field measurement on vehicles, no significant problems or concerns were experienced in conducting the stall idle, or snap idle tests. These two tests could be conducted with the vehicle

TABLE 3-2. SCREENING TEST RESULTS (OPACIMETER DATA)

	Engine			Smoke Opacity (Opacimeter Measurement)							
				Full Power Acceleration		Lug-Down		Stall Idle		Snap Idle	
Truck ID	Make	Model	Aspir.*	Peak	Stab.	Peak	Stab.	Peak	Stab.	Peak	Stab.
PASADENA-01	CAT	3208	NA	8 P+	6 P			8 P	3 P	8 P	2 P
PASADENA-02**	CAT	3208	TC	40 F++	10 F			38 F	12 F	54 F	2 P
PASADENA-03	DDA	6V71	NA	26 P	1 P			24 P	4 P	3 P	1 P
PASADENA-04	CAT	3208T	TC	21 P	5 P			32 P	8 P	20 P	8 F
PASADENA-05	CAT	3208	NA	24 P	9 F			12 P	3 P	10 P	8 F
PASADENA-06	CAT	3208	NA	20 P	6 P			16 P	6 P	20 P	13 F
PASADENA-07	DDA	6V71	NA	54 F	18 F			56 F	33 F	40 P	6 P
PASADENA-08**	DDA	8.2L	NA	35 P	25 F			25 P	25 F	32 P	8 F
PASADENA-09	CAT	3208	NA	10 P	6 P			14 P	3 P	12 P	9 F
PASADENA-10	GMC	8.2L	TC	56 F	8 F			55 F	12 F	50 F	4 P
LA USPS-01	MACK	300 HP	TC/AAAC	20 P	5 P	60 F	4			96 F	5 P
LA USPS-02	MACK	300 HP	TC/AAAC	36 F	4 P	22 F	6			96 F	4 P
LA USPS-03**	CUMM	NTC 300	TC/JWAC	11 P	4 P	12 P	5			26 P	6 P
LA USPS-04	CUMM	NTC 300	TC/JWAC	24 P	6 P	20 P	8			24 P	6 P
LA USPS-05**	MACK	300 HP	TC/AAAC	28 P	8 F	15 P	4			98 F	4 P
LA USPS-06	DDA	8.2L	TC	26 P	4 P			30 P	18 F	20 P	5 P
LA USPS-07	IHC	6.2L	NA	23 P	15 F			25 P	10 P	38 P	6 P
LA USPS-08	IHC	6.2L	NA	14 P	6 P			10 P	6 P	16 P	3 P
LA USPS-09	IHC	6.2L	NA	5 P	1 P			16 P	4 P	14 P	2 P
LA USPS-10	DDA	8.2L	TC	34 P	20 F			9 P	2 P	34 P	0
LA DPW-01	DDA	6V92TAC	TC/JWAC	22 P	6 P	42 F	10			20 P	4 P
LA DPW-02**	CUMM	350NTC	TC/JWAC	24 P	4 P	40 F	6			22 P	2 P
LA DPW-03**	DDA	6V92TAC	TC/JWAC	90 F	20 F	98 F	32			94 F	16 F
LA DPW-04	DDA	6V92TAC	TC/JWAC	7 P	1 P	52 F	2			14 P	4 P
LA DPW-05	DDA	6V92TAC	TC/JWAC	9 P	2 P	40 F	6			6 P	1 P
LA DPW-06	DDA	6V92TAC	TC/JWAC	68 F	10 F	78 F	10			60 F	6 P
LA SAN-07	CUMM	L10	TC/JWAC	20 P	8 F			26 P	14 F	38 P	18 F
LA SAN-08	CUMM	350NTC	TC/JWAC	14 P	3 P	15 P	5			24 P	6 P
LA SAN-09	CUMM	L10	TC/JWAC	20 P	6 P			25 P	9 P	32 P	9 F
SCE-01	CUMM	350NTC	TC/JWAC	23 P	8 F	20 P	4			37 P	2 P
SCE-02**	CUMM	350NTC	TC/JWAC	14 P	8 F	8 P	4			56 F	7 F
SCE-03**	CUMM	350NTC	TC/JWAC	10 P	2 P	8 P	4			29 P	1 P
SCE-04	CUMM	350NTC	TC/JWAC	11 P	5 P	7 P	2			72 F	2 P
SCE-05 (L)	DDA	8V53	NA	34 P	1 P	4 P	2			9 P	1 P
SCE-05 (R)	DDA	8V53	NA	31 P	10 F	26 F	2			12 P	2 P
SCE-06	CUMM	350NTC	TC/JWAC	14 P	0 P	26 F	4			24 P	2 P
SCE-07	CAT	V6-36	NA	6 P	2 P	12 P	2			8 P	2 P

(Continued)

TABLE 3-2. (Continued)

				Smoke Opacity (Opacimeter Measurement)							
	Engine			Full Power Acceleration		Lug-Down		Stall Idle		Snap Idle	
Truck ID	Make	Model	Aspir.*	Peak	Stab.	Peak	Stab.	Peak	Stab.	Peak	Stab.
CALTRANS-01	CAT	3208	NA	10 P	2 P			6 P	2 P	5 P	1 P
CALTRANS-02	CAT	3208	NA	4 P	4 P			6 P	4 P	5 P	1 P
CALTRANS-03**	IH	DT466	TC	44 F	8 F	50 F	12			55 F	1 P
CALTRANS-04	IH	DT466	TC	24 P	3 P	8 P	5			24 P	1 P
CALTRANS-05	CAT	3208	NA	9 P	4 P			24 P	3 P	20 P	5 P
CALTRANS-06	IH	DT466	TC	20 P	5 P			20 P	6 P	20 P	2 P
CALTRANS-07	CAT	3208	NA	14 P	8 F			16 P	8 P	40 P	4 P
LA GMC-01	CUMM	235	TC	44 F	4 P	6 P	2			60 F	6 P
LA GMC-02	CUMM	400NTC	TC	8 P	1 P	8 P	4			10 P	1 P
LA GMC-03**	CUMM	335NTC	TC	100 F	96 F	28 F	24			91 F	13 F
LA GMC-04	CAT	3406	TC	40 F	2 P	8 P	5			76 F	6 P
LA GMC-05	CAT	3406	TC	86 F	20 F	16 P	10			92 F	9 F
LA GMC-06	CAT	3408	TC	88 F	4 P	80 F	20			50 F	2 P
LA GMC-07	CUMM	290NT	TC	31 P	1 P	70 F	10			80 F	1 P
LA GMC-08**	DDA	8V71T	TC	75 F	75 F	58 F	42			85 F	2 P
LA GMC-09	CAT	1693	TC	20 P	6 P	20 P	5			15 P	6 P

* NA: Naturally aspirated.
TC: Turbocharged.
JWAC: Jacket water aftercooler.
AAAC: Air-to-air aftercooler.

** Selected for emissions testing at HSLD.

\+ Passes Task 2 failure criteria.
++ Fails Task 2 failure criteria.

TABLE 3-3. SCREENING TEST RESULTS (VISUAL OPACITY ESTIMATES)

	Engine			Smoke Opacity (Visual Estimate)							
				Full Power Acceleration		Lug-Down		Stall Idle		Snap Idle	
Truck ID	Make	Model	Aspir.*	Peak	Stab.	Peak	Stab.	Peak	Stab.	Peak	Stab.
PASADENA-01	CAT	3208	NA	15 P+	5 P			5 P		2 P	
PASADENA-02**	CAT	3208	TC	40 F++	25 F			40 F	5 P	50 F	2 P
PASADENA-03	DDA	6V71	NA	10 P	2 P			10 P	5 P	5 P	5 P
PASADENA-04	CAT	3208T	TC	40 F	10 F			20 P	10 P	25 P	10 F
PASADENA-05	CAT	3208	NA	20 P	2 P			15 P	10 P	20 P	10 F
PASADENA-06	CAT	3208	NA	20 P	8 F			25 P	10 P	15 P	10 F
PASADENA-07	DDA	6V71	NA	40 F	20 F			40 F	40 F	45 F	10 F
PASADENA-08**	DDA	8.2L	NA	50 F	35 F			60 F	50 F	45 F	20 F
PASADENA-09	CAT	3208	NA	10 P	8 F			12 P	2 P	10 P	5 P
PASADENA-10	GMC	8.2L	TC	25 P	10 F			35 P	15 F	35 P	5 P
LA USPS-01	MACK	300 HP	TC/AAAC	10 P	5 P		5			80 F	5 P
LA USPS-02	MACK	300 HP	TC/AAAC	10 P	5 P		5			90 F	5 P
LA USPS-03**	CUMM	NTC 300	TC/JWAC	25 P	8 F		5			20 P	5 P
LA USPS-04	CUMM	NTC 300	TC/JWAC	30 P	8 F	20 P	10			25 P	5 P
LA USPS-05**	MACK	300 HP	TC/AAAC	15 P	8 F		5			90 F	5 P
LA USPS-06	DDA	8.2L	TC	20 P	10 F			40 F	30 F	25 P	5 P
LA USPS-07	IHC	6.2L	NA	10 P	8 F			15 P	10 P	25 P	8 F
LA USPS-08	IHC	6.2L	NA	10 P	5 P			10 P	5 P	15 P	5 P
LA USPS-09	IHC	6.2L	NA	10 P	5 P			15 P	5 P	8 P	5 P
LA USPS-10	DDA	8.2L	TC	40 F	5 P			15 P	15 F	75 F	10 F
LA DFW-01	DDA	6V92TAC	TC/JWAC	22 P	6 P	40 F	8			20 P	4 P
LA DFW-02**	CUMM	350NTC	TC/JWAC	24 P	4 P	40 F	8			22 P	8 F
LA DFW-03**	DDA	6V92TAC	TC/JWAC	90 F	20 F	40 F	20			94 F	16 F
LA DFW-04	DDA	6V92TAC	TC/JWAC	7 P	1 P	30 F	15			14 P	4 P
LA DFW-05	DDA	6V92TAC	TC/JWAC	9 P	2 P	10 P	5			6 P	1 P
LA DFW-06	DDA	6V92TAC	TC/JWAC	68 F	10 F	60 F	20			60 F	6 P
LA SAN-07	CUMM	L10	TC/JWAC	20 P	8 F			26 P	14 F	38 P	18 F
LA SAN-08	CUMM	350NTC	TC/JWAC	19 P	9 F	20 P	10			25 P	6 P
LA SAN-09	CUMM	L10	TC/JWAC	20 P	6 P			30 P	20 F	32 P	8 F
SCE-01	CUMM	350NTC	TC/JWAC	23 P	8 F	20 P	4			37 P	2 P
SCE-02**	CUMM	350NTC	TC/JWAC	14 P	8 F	8 P	4			53 F	8 F
SCE-03**	CUMM	350NTC	TC/JWAC	12 P	2 P	8 P	4			34 P	1 P
SCE-04	CUMM	350NTC	TC/JWAC	11 P	5 P	7 P	2			74 F	2 P
SCE-05(L)	DDA	8V53	NA	33 P	5 P	12 P	2			12 P	2 P
SCE-05(R)	DDA	8V53	NA	40 F	10 F	30 F	10			25 P	5 P
SCE-06	CUMM	350NTC	TC/JWAC	14 P	0 P	26 F	4			24 P	2 P
SCE-07	CAT	V6-36	NA	6 P	2 P	12 P	2			8 P	2 P

(Continued)

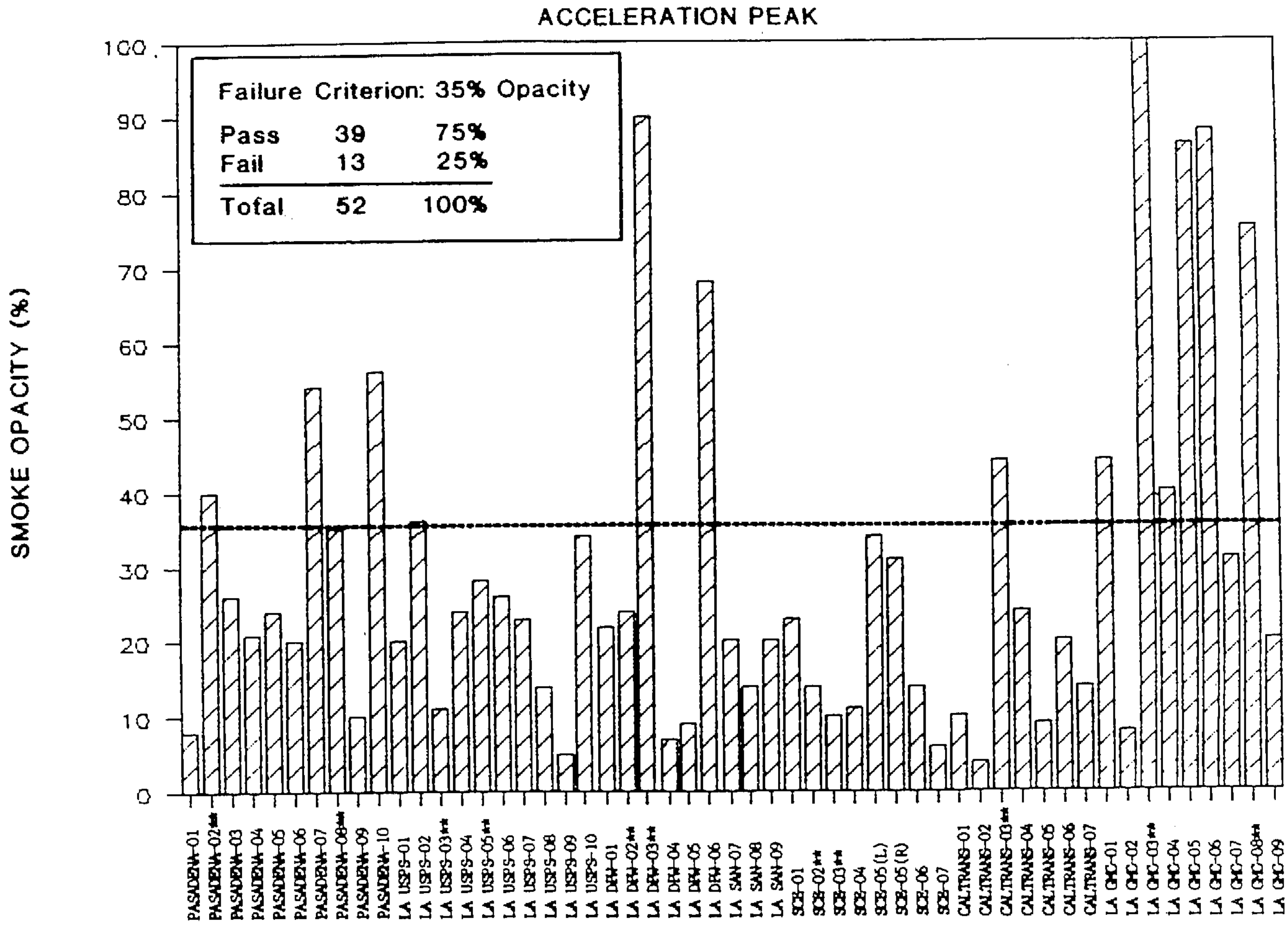
TABLE 3-3. (Continued)

	Engine			Smoke Opacity (Visual Estimate)							
				Full Power Acceleration		Lug-Down		Stall Idle		Snap Idle	
Truck ID	Make	Model	Aspir.*	Peak	Stab.	Peak	Stab.	Peak	Stab.	Peak	Stab.
CALTRANS-01	CAT	3208	NA	8 P	2 P			6 P	2 P	18 P	1 P
CALTRANS-02	CAT	3208	NA	4 P	4 P			6 P	4 P	5 P	1 P
CALTRANS-03**	IH	DT466	TC	44 F	8 F	36 F				55 F	1 P
CALTRANS-04	IH	DT466	TC	24 P	1 P	10 P				24 P	1 P
CALTRANS-05	CAT	3208	NA	9 P	4 P			24 P	3 P	20 P	5 P
CALTRANS-06	IH	DT466	TC	20 P	5 P			20 P	6 P	20 P	1 P
CALTRANS-07	CAT	3208	NA	14 P	8 F			16 P	8 P	40 P	4 P
LA GMC-01	CUMM	235	TC	44 F	4 P	40 F				60 F	6 P
LA GMC-02	CUMM	400NTC	TC	8 P	1 P					10 P	1 P
LA GMC-03**	CUMM	335NTC	TC	100 F	90 F	20 P				90 F	13 F
LA GMC-04	CAT	3406	TC	40 F	10 F	10 P				76 F	6 P
LA GMC-05	CAT	3406	TC	86 F	20 F	58 F				92 F	9 F
LA GMC-06	CAT	3408	TC	60 F	5 P	90 F	30			40 P	5 P
LA GMC-07	CUMM	290NT	TC	50 F	5 P	50 F	20			60 F	5 P
LA GMC-08**	DDA	8V71T	TC	50 F	50 F	50 F	50			90 F	5 P
LA GMC-09	CAT	1693	TC	10 P	5 P	15 P	10			25 P	5 P

* NA: Naturally aspirated.
TC: Turbocharged.
JWAC: Jacket water aftercooler.
AAAC: Air-to-air aftercooler.

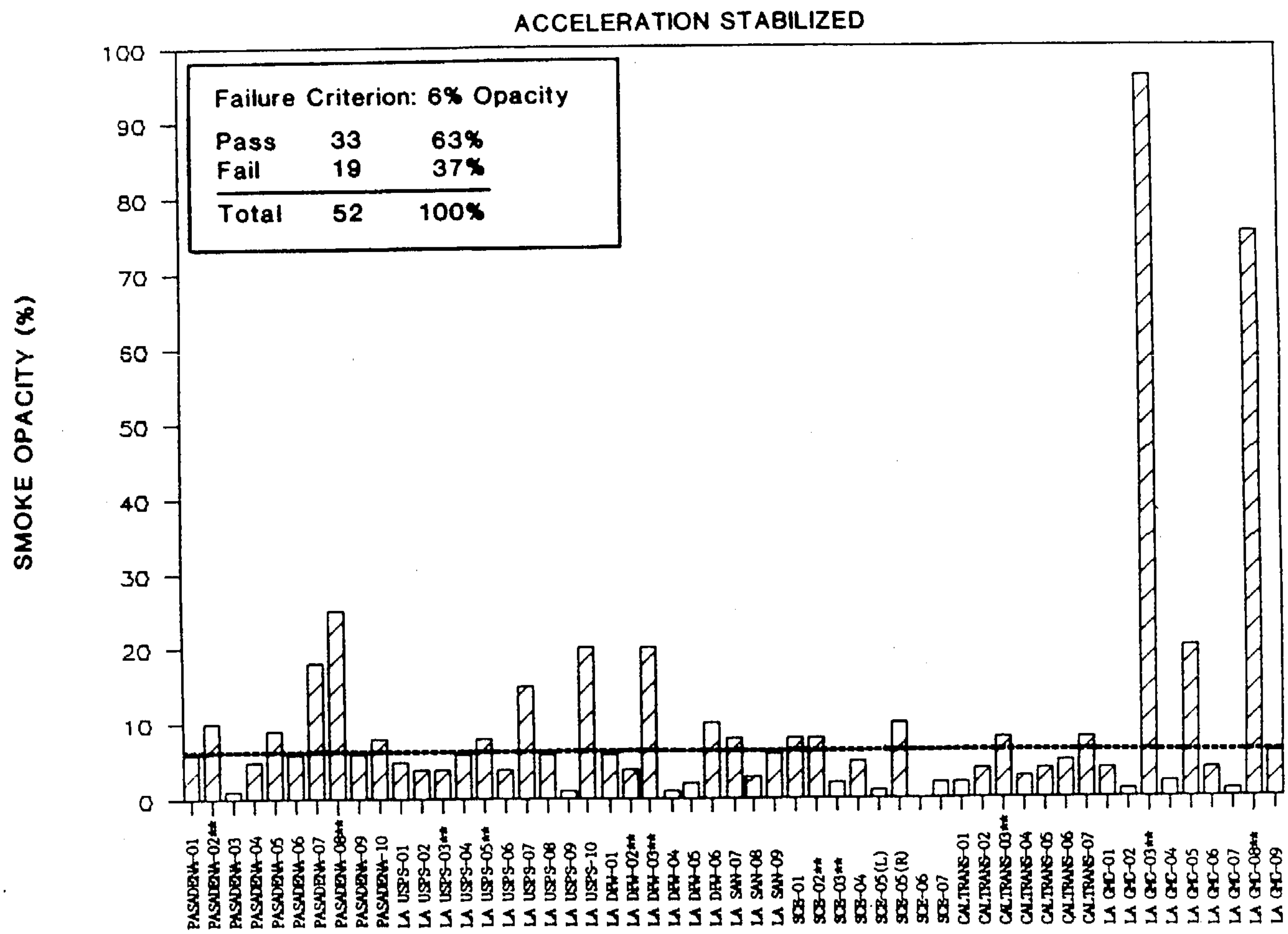
** Selected for emissions testing at HSLD.

\+ Passes Task 2 failure criteria.
++ Fails Task 2 failure criteria.



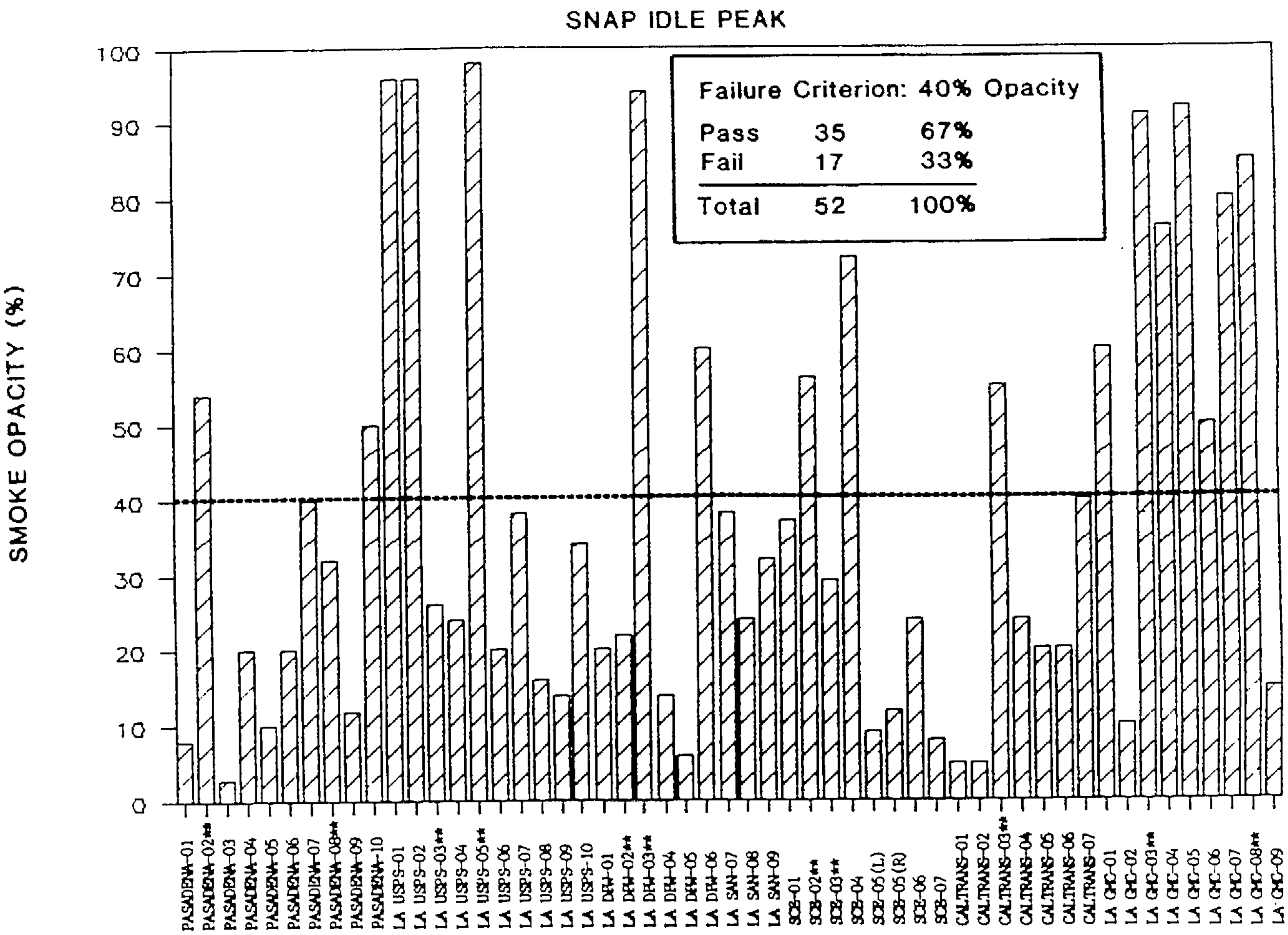
**Scheduled for testing at HSLD.

Figure 3-4. Bar Chart of Peak Acceleration Smoke Opacities from the Field Screening



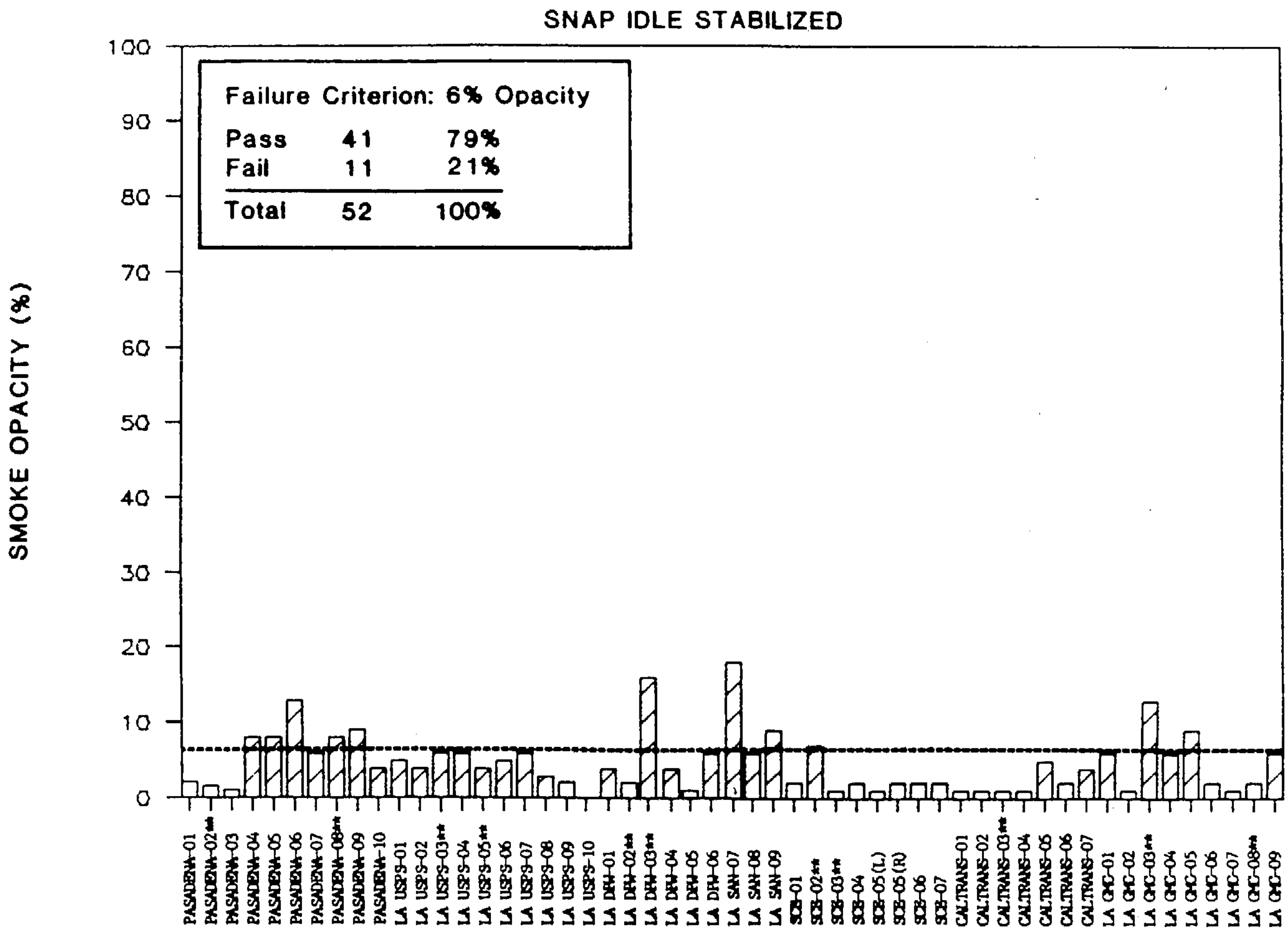
**Scheduled for testing at HSLD.

Figure 3-5. Bar Chart of Stabilized Acceleration Smoke Opacities from the Field Screening



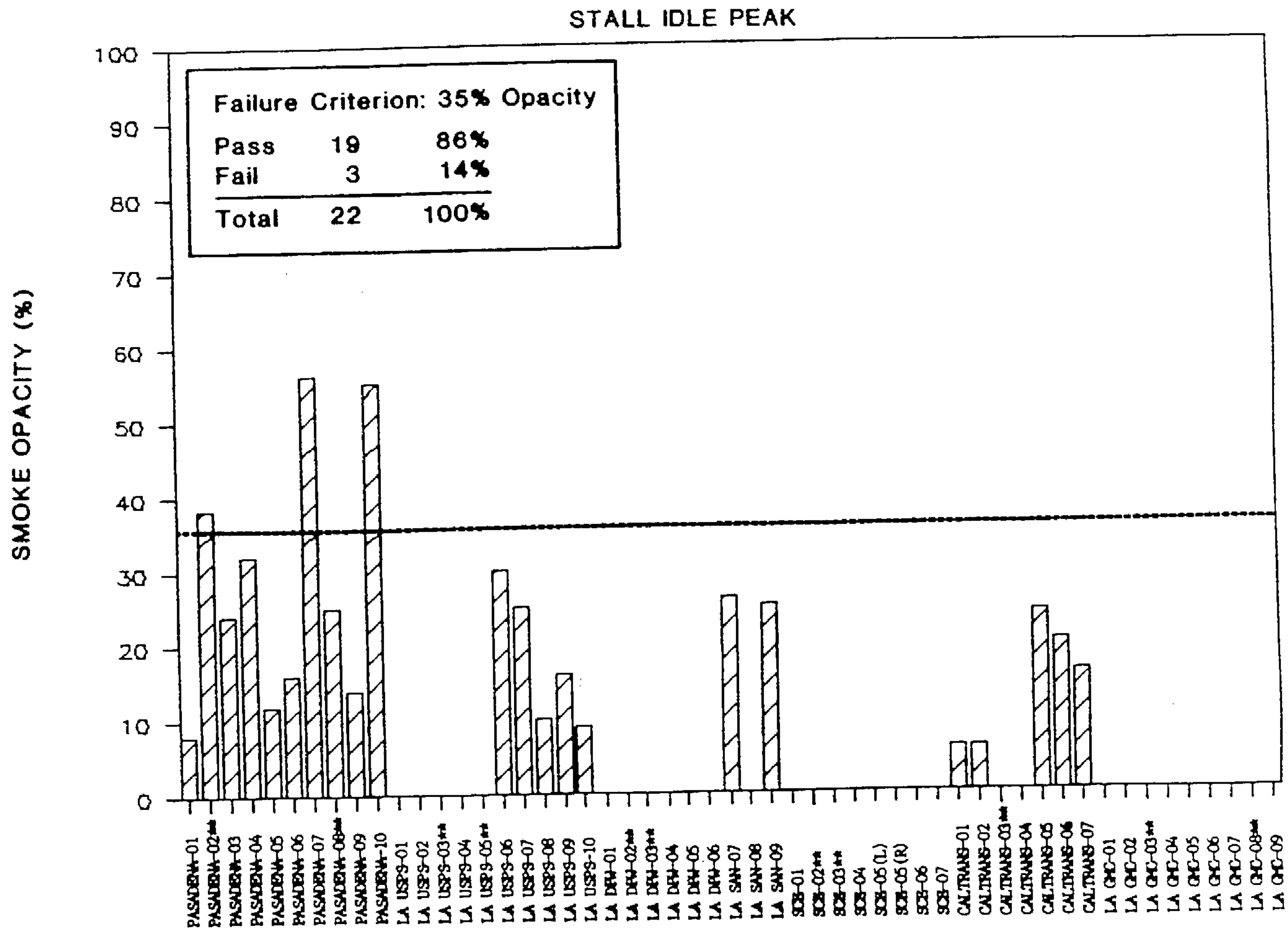
**Scheduled for testing at HSLD.

Figure 3-6. Bar Chart of Peak Snap Idle Smoke Opacities from the Field Screening



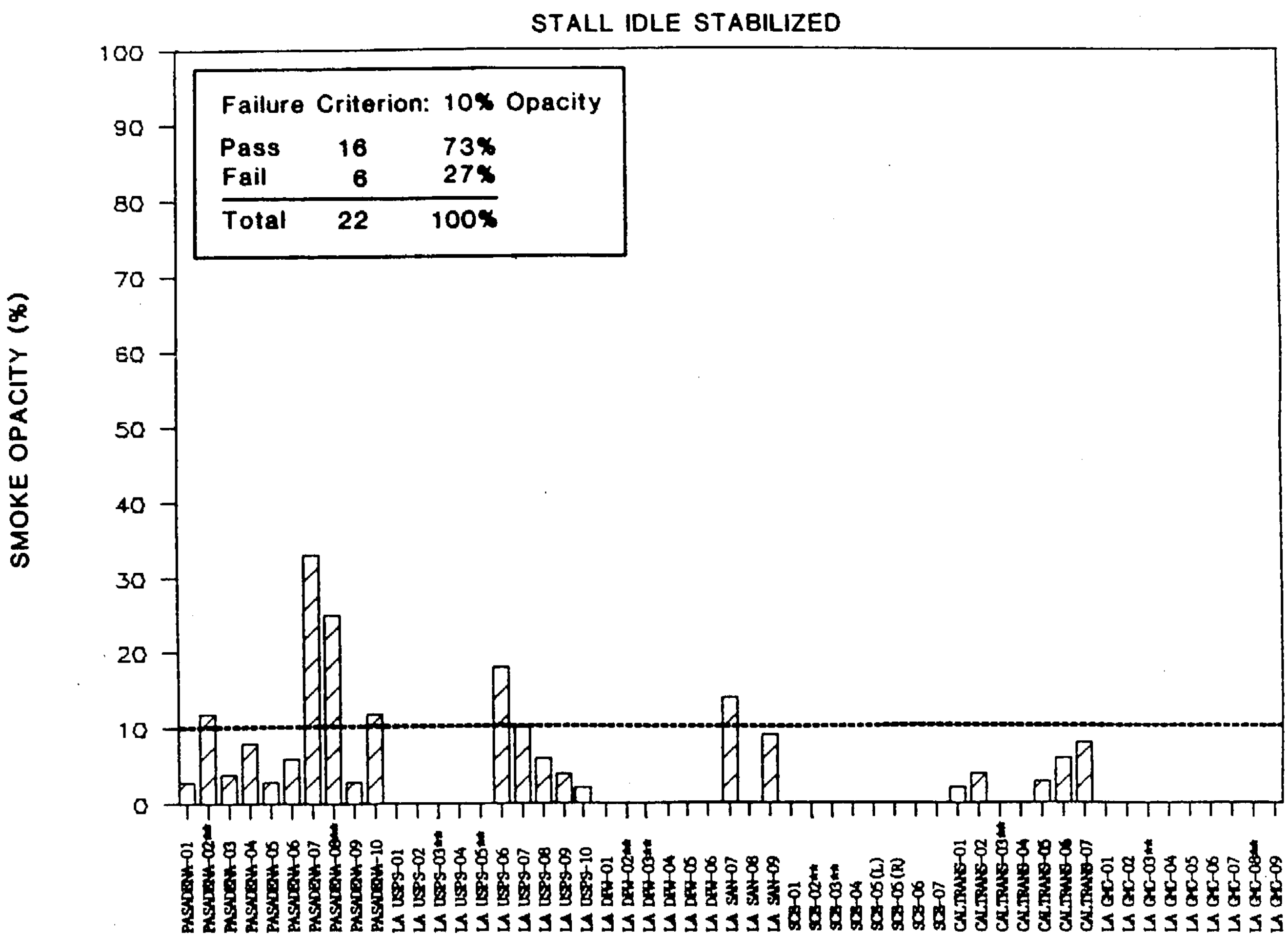
**Scheduled for testing at HSLD.

Figure 3-7. Bar Chart of Stabilized Snap Idle Smoke Opacities from the Field Screening



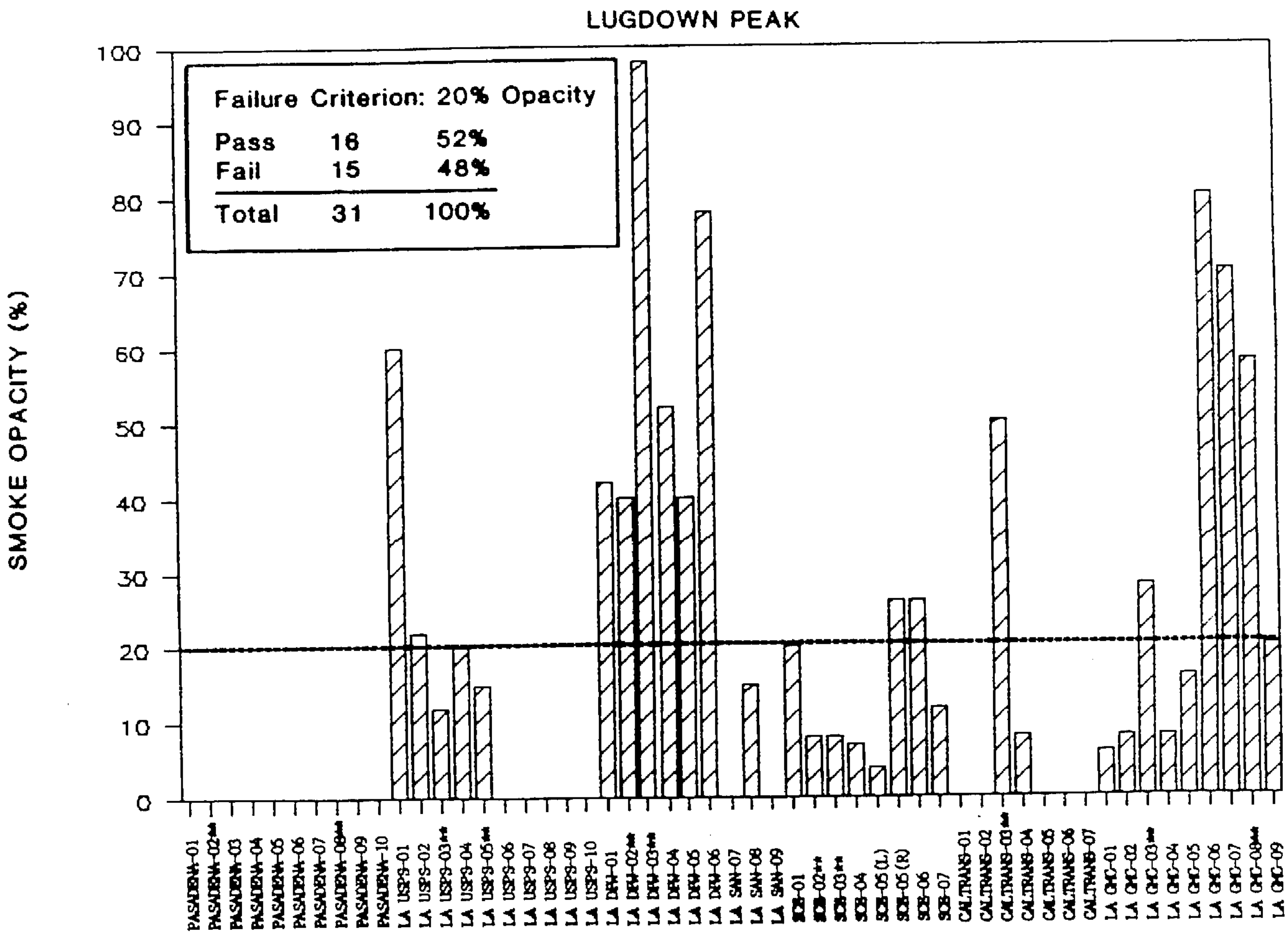
**Scheduled for testing at HSLD.

Figure 3-8. Bar Chart of Peak Stall Idle Smoke Opacities from the Field Screening



**Scheduled for testing at HSLD.

Figure 3-9. Bar Chart of Stabilized Stall Idle Smoke Opacities from the Field Screening



**Scheduled for testing at HSLD.

Figure 3-10. Bar Chart of Peak Lug-Down Smoke Opacities from the Field Screening standing still. With the full-power acceleration test, it was necessary to have sufficient room to accelerate--and to slow down afterwards--without undue risk. Although no incidents were experienced in our screening tests, safety and the provision of an appropriate test area would be a concern in any widespread application of this procedure.

Significant difficulties were experienced with the lug-down test for manual transmission vehicles. As noted above, the driver action required for this test (braking with the left foot while holding full accelerator with the right) is "unnatural", and many drivers either misunderstood it or were reluctant to do it. This test also imposes a significant strain on the brakes and transmission, and in some high-powered trucks it may cause the drive wheels to slip and spin if the brakes are unevenly adjusted.

The acceleration/lug-down test requires much more space than the acceleration alone, since the lug-down requires 3-5 seconds of operation at or near rated engine speed. In addition to problem of sufficient space, the effects of this type of operation on safety (especially in a congested area such as a truck depot) would be a significant concern. Shortage of space often resulted in the drivers having to apply the brakes too quickly to give a smooth reduction in engine speed. This led to "overshooting" the target of 60% of rated speed, and often caused stumbling and considerable excess black smoke. This greatly degraded the precision of the test. This problem, rather than an actual emissions failure, is considered to be the cause of most of the numerous high lug-down smoke values shown in Figure 3-10. A fuller analysis of the correspondence between these tests and the better-controlled engine-dynamometer tests is given in Section 5.2.

4.0 PERIODIC I/M TESTS AND DYNAMOMETER EMISSIONS MEASUREMENTS

As a result of the screening tests described in the previous section, eleven trucks were selected for more extensive testing at ARB's Haagen-Smit Laboratory. These trucks were delivered to the laboratory one at a time to be tested using the smoke opacity tests from the Periodic I/M Test (PIMT) procedure, and a modified chassis-dynamometer version of the Federal 13-mode emissions test procedure. The latter test included measurements of HC, CO, NO_x, and particulate emissions, fuel economy, and road horsepower (power delivered to the dynamometer rolls). Concentrations of HC, CO, CO_2, and NO_x in the raw exhaust were also measured and recorded. Haagen-Smit laboratory personnel were responsible for all measurements and data recording for these tests.

Based on the results of these tests, six of the higher-emitting trucks in the sample were sent out for diagnosis and repair of emissions-related malfunctions. These trucks were then returned to the laboratory for another round of testing.

4.1 Selection of Trucks for Testing

Trucks to be tested at HSLD were selected on the basis of their screening test results and their suitability for testing. Some trucks, such as garbage trucks (with their high vertical clearance), street sweepers, and trucks with dual exhausts were impractical to test on the HSLD emissions setup. In choosing the trucks to be tested, we attempted to pick a representative range of expected emissions levels, from very low emitters to extremely high emitters, with a selection of moderately low and high emitters in between in order to assess the ability of the test procedures to discriminate between them. A larger number of high emitters than low or moderate emitters were selected, however, since half of the trucks were to be repaired and retested. It would make no sense to repair and retest a low-emitting vehicle. Table 4-1 lists the technical characteristics of the trucks selected for this test program, and summarizes their test results from the screening tests.

TABLE 4-1. TRUCKS SELECTED FOR TESTING AT HSLD

Truck ID	Engine				Trans.	Mileage	Road Tests—Smoke Opacity (%) (Opacimeter Measurement)							
							Full Power Acceleration		Lug-Down		Stall Idle		Snap Idle	
	Make	Model	Year	Aspir.			Peak	Stab.	Peak	Stab.	Peak	Stab.	Peak	Stab.
Pasadena-02	CAT	3208	1982	TC	Auto	10,732	40 F	10 F			38 F	12 F	54 F	2 P
Pasadena-08	DDA	8.2L	1982	NA	Auto	16,709	35 P	25 F			25 P	25 F	32 P	8 F
LA USPS-03	CUMM	NTC 300	1981	TC/JWAC	Manual	154,379	11 P	4 P	12 P	5			26 P	6 P
LA USPS-05	MACK	300 HP	1984	TC/AAAC	Manual	54,160	28 P	8 F	15 P	4			98 F	4 P
LA DPW-02	CUMM	350NTC	1982	TC/JWAC	Manual	34,820	24 P	4 P	40 F	6			22 P	2 P
LA DPW-03	DDA	6V92TAC	1980	TC/JWAC	Manual	100,026	90 F	20 F	98 F	32			94 F	16 F
SCE-02	CUMM	350NTC	1980	TC/JWAC	Manual	164,396	14 P	8 F	8 P	4			56 F	7 F
SCE-03	CUMM	350NTC	1984	TC/JWAC	Manual	83,305	10 P	2 P	8 P	4			29 P	1 P
CALTRANS-03	IH	DT466		TC	Manual	33,965	44 F	8 F	50 F	12			55 F	1 P
LA GMC-03	CUMM	335NTC	1976	TC	Manual	514,882	100 F	96 F	28 F	24			91 F	13 F
LA GMC-08	DDA	8V71T	1977	TC	Manual	100,006	75 F	75 F	58 F	42			85 F	2 P

Based on the screening test results, trucks Pasadena-08, LA DPW-03, LA GMC-03, and LA GMC-08 were projected to be high to very high emitters, as indicated in Table 4-1. Each of these trucks had failed all or nearly all of the screening tests by a large margin. Similarly, trucks Pasadena-02, LA USPS-05, SCE-02, and LA DPW-02 were projected to be moderately high emitters, having failed one or more screening tests by a moderate amount. Truck LA DPW-02 was considered a moderately low emitter (having failed only the lug-down test, in what was considered a questionable result). Trucks LA USPS-03 and SCE-03 were projected to be low and very low emitters, respectively, having passed all the tests--the latter by a very wide margin.

4.2 Periodic I/M Tests

The PIMT test procedures used in the validation testing included only the dynamometer smoke opacity measurements described in Section 2.2. Due to the potential problems of diesel particulate fouling in existing I/M-type analyzers, NO_x and HC concentration measurements were made as part of the gaseous/particulate emissions procedure rather than during the PIMT. Visual and functional inspection of emissions controls was considered to be inapplicable, as these current-technology vehicles were not equipped with trap-oxidizers, EGR valves, electronic control systems, or other readily inspectable emissions controls. Inspection of the fuel pump seals would have been possible, but would reveal nothing, as fuel pump adjustments are not presently required to be sealed.

To make these measurements, the truck was brought in and positioned with its drive wheels on the dynamometer rolls, then firmly tied down to prevent it from running away if it slipped off. This setup is shown in Figure 4-1. To assure adequate cooling during prolonged test runs, the radiator hoses were re-routed to include a liquid-liquid heat exchanger in series with the radiator. This was needed primarily for the 14-mode emissions tests (which involved considerable periods of full-power and full-torque operation), and for the first few PIMTs, during which the dynamometer stability problems resulted in some very long periods of full-power operation. For routine testing using the PIMT, a powerful fan blowing across the radiator should provide adequate cooling.

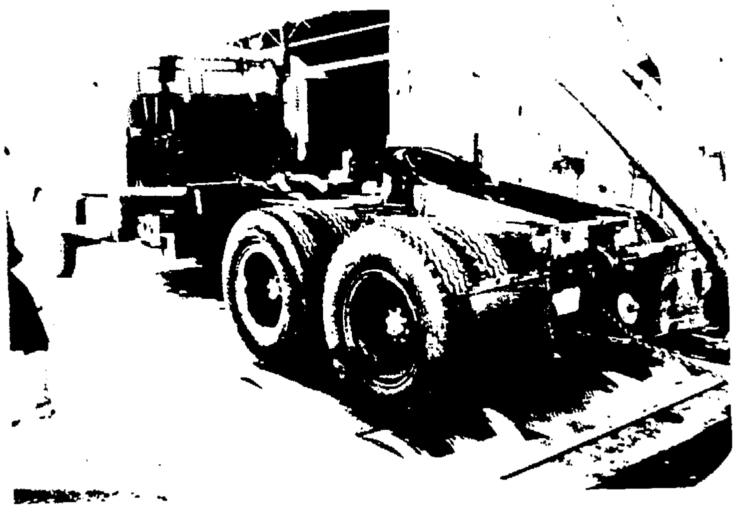


Figure 4-1. Laboratory Dynamometer Emissions Test Setup

To make the smoke opacity measurements, the Wager portable opacimeter was installed on the stack and checked for zero and span. Since these tests often involved considerable periods at high smoke opacity, fouling of the smokemeter lenses with soot became a problem. This was alleviated by sealing the space around the edges of the opacimeter light shields with tape, and introducing a small continuous airflow from the laboratory compressed air supply.

As it was received from the factory, the Wager opacimeter was equipped with an automatic timer to conserve batteries. This timer shut off the meter ten minutes after it was turned on, whether or not the meter was in use. This required that the meter be re-zeroed each time. Since the opacity measurements took longer than ten minutes to complete, this was a major nuisance. The problem was resolved by disabling the timer, following the manufacturer's instructions.

The instructions for making the smoke opacity measurements were documented in a memo to the laboratory staff. This memorandum is given in Appendix B, and is briefly summarized here. Once the smokemeter was attached, the engine was started and warmed up to operating temperature. It was then shut down to allow the zero on the opacimeter to be set. The engine was then restarted and the idle smoke opacity recorded. The engine was then accelerated to the no-load governor speed with the drivetrain in gear, but with no load on the dynamometer. The dynamometer load was then increased until the engine was developing full power at rated speed. The smoke opacity at this point was recorded. The load was then increased further to reduce the engine speed progressively to 90%, 80%, 70%, and 60% of the rated speed (or the maximum torque speed, whichever was higher), recording the opacity at each point. To simulate road-load operation, a second set of opacity measurements was made at each speed with the dynamometer set to 75% of the maximum power measured at that speed.

Following the lug-down and road-load opacity measurements, the dynamometer was set to produce approximately 50% of the maximum power with the engine running at rated speed in a given gear. The truck was then accelerated from idle (with the wheels stopped) to rated speed in that gear as rapidly as possible. Opacimeter output was recorded with a strip-chart recorder, so that the peak and stabilized smoke opacities could be identified, in the same way as for the full-power acceleration procedure in the ROC. Finally, a snap idle test (following the same procedure as the ROC) was made.

Table 4-2 summarizes the smoke opacity results from the PIMT procedure. Six trucks were repaired and retested; for these trucks, both pre-repair (Test 1) and post-repair (Test 2) results are shown. The pass/fail determination for each truck in each test mode is also shown in the table. For ease of comparison, the composite gaseous and particulate emissions measurements from the chassis 13-mode test are also listed in the table. These measurements are discussed in greater detail in the next section.

As Table 4-2 indicates, smoke opacity data are unavailable for one test on truck Pasadena-08. These data were taken, but the laboratory was unable to locate the data sheet later. Smoke opacity data at the 60% speed point are also shown as not available for a number of trucks. For these trucks, the maximum torque speed (or the transmission shift point, for trucks with automatic transmissions) was at or above 70% of the rated speed, so the lower speed was not used.

4.3 Gaseous and Particulate Emissions Tests

Gaseous and particulate emissions from the trucks tested at HSLD were measured by a modified version of the old Federal 13-mode steady-state procedure. The 13-mode procedure was modified by adding a 14th mode (governor speed at zero load), and by performing the tests on a chassis dynamometer (i.e., with the engine still in the vehicle) rather than an engine dynamometer. Table 4-3 lists the operating modes included in the modified test procedure. Trucks were run in gear on the chassis dynamometer, while the dynamometer load and truck accelerator position were adjusted to give the required speed and power output. Emissions measurements were taken once the

TABLE 4-2. RESULTS OF DYNAMOMETER SMOKE OPACITY TESTS FROM THE PIMT

		Dynamometer Tests--Smoke Opacity (%) (Opacimeter Measurement)															
		Full Power Lug-Down						3/4 Power Lug-Down						Full Power Acceleration		Snap Idle	
Truck ID	Test No.	100	90	80	70	60	P/F	100	90	80	70	60	P/F	Peak	Stab.	Peak	Stab.
Pasadena-02	1	10	11	14	24	39	F	4	3	4	7	11	P	82 F	6 P	72 F	7 F
Pasadena-02	2	3	2	2	5	11	P	3	2	2	3	3	P	28 P	3 P	27 P	3 P
Pasadena-08	1	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA		NA	NA	NA	NA
Pasadena-08	2	12	13	15	16	NA	P	2	2	2	2	NA	P	15 P	1 P	14 P	2 P
LA USPS-03	1	4	3	3	3	4	P	4	4	4	4	5	P	8 P	2 P	20 P	2 P
LA USPS-05	1	7	7	7	8	15	P	3	3	3	4	10	P	50 F	5 P	66 F	6 P
LA USPS-05	2	3	3	3	4	9	P	2	2	2	2	4	P	32 P	3 P	46 F	3 P
LA DPW-02	1	4	2	3	4	12	P	2	2	3	4	9	P	12 P	3 P	22 P	2 P
LA DPW-03	1	1	1	2	4	11	P	1	1	1	3	6	P	96 F	2 P	94 F	4 P
SCE-02	1	3	3	3	4	9	P	1	1	2	2	4	P	40 F	2 P	48 F	2 P
SCE-03	1	0	1	1	4	NA	P	0	2	0	3	NA	P	2 P	1 P	5 P	1 P
CALTRANS-03	1	1	1	1	1	NA	P	1	1	1	2	NA	P	32 P	3 P	33 P	4 P
CALTRANS-03	2	1	2	3	6	NA	P	2	2	2	4	NA	P	40 F	2 P	47 F	1 P
LA GMC-03	1	14	26	24	22	34	F	4	4	4	5	5	P	98 F	10 F	100 F	12 F
LA GMC-03	2	8	6	5	6	4	P	3	2	2	3	2	P	37 F	6 P	52 F	5 P
LA GMC-08	1	2	2	5	9	NA	P	0	3	3	6	NA	P	80 F	4 P	15 P	5 P
LA GMC-08	2	0	0	1	2	NA	P	0	0	0	1	NA	P	32 P	3 P	7 P	3 P

engine condition stabilized. The variables measured included the engine RPM, fuel flow, air flow, and air temperature, and the concentrations of CO_2, CO, HC, and NO_x in the raw exhaust. A portion of the exhaust was conducted to a dilution tunnel for particulate measurements. Emission rates in grams/hour for each mode were calculated in accordance with Federal regulations (40 CFR 86).

Cycle-composite values of HC, CO, NO_x, and particulate emissions were calculated as for the 13-mode cycle: by weighting the value for each non-idle mode by 0.08 and for each idle mode by 0.067 and summing. Emission factors, expressed in grams per road horsepower hour (g/RHP-hr) and grams per pound of fuel used, were calculated for the cycle composite emissions and for each mode separately. Cycle composite emissions in g/RHP-hr for the 13-mode cycle were summarized in Table 4-2. The same data, together with the fuel-specific emissions, are given in Table 4-3. Measured and calculated emissions data for each vehicle in each mode are listed in the Appendix. Analysis of these data is deferred to Section Five.

The results of these tests should be interpreted cautiously. First, the chassis dynamometer procedure could only measure road horsepower, rather than engine brake horsepower. This means that variations in drivetrain design or efficiency could affect the results. Second, HC and PM emissions measured even on the engine-dynamometer version of the 13-mode cycle have been shown to correlate poorly with emissions measured in the Federal Heavy-Duty Transient Test, which is considered to be much more representative of in-use operation. NO_x emissions, on the other hand, correlate very well between the two tests.

A test procedure involving transient operation over a defined test cycle would probably have produced more representative HC and PM emissions data. Such a procedure was beyond the capabilities of the equipment available for this test program, however. ARB and the Southern California Rapid Transit District are jointly funding the construction of a transient-capable heavy-duty dynamometer test facility for emissions measurements. It is recommended that subsequent research in this area make use of this or a

TABLE 4-3. CHASSIS 14-MODE TEST CYCLE

Mode	Speed	Load
1	Idle	0%
2	Rated	2%
3	Rated	25%
4	Rated	50%
5	Rated	75%
6	Rated	100%
7	Idle	0%
8	Intermediate*	100%
9	Intermediate	75%
10	Intermediate	50%
11	Intermediate	25%
12	Intermediate	2%
13	Idle	0%
14	Governor Limit	0%

* Maximum torque speed or 60% of rated speed, whichever is higher.

similar facility. Alternatively, it appears technically feasible to develop portable instruments for measuring gaseous and particulate emissions from vehicles operating on the road. This approach could provide a great deal of information, while avoiding the problems and expense of brining trucks to a central test facility.

4.4 Effects of Repairs on Emissions

Six of the eleven trucks tested were sent out for emissions-related repairs, and then retested. Table 4-4 summarizes the repairs done on each vehicle, and the results. As this table indicates, the effectiveness of the repairs in reducing emissions varied considerably. The individual vehicle results are discussed below.

Vehicle PASADENA-02--This truck was a heavy smoker with very high particulate emissions. NO_x emissions were also rather high, at 7.8 g/RHP-hr compared to the California standard of 5.0 g/BHP-hr for this 1982 engine. The road-specific fuel consumption measured on this truck was also very high--more than 50% greater than the typical brake-specific fuel consumption of 0.4 lb/BHP-hr measured on an engine dynamometer. It appears that some of the high emissions from this vehicle may have been due to an inefficient driveline, resulting in less of the engine power output being transmitted to the wheels.

This truck suffered from overheating problems during testing at HSLD. Subsequently, after it was returned to the City of Pasadena, it was found that an incorrect cylinder head gasket had been installed in the engine, blocking some of the cooling passages and presumably contributing to the overheating problem. This problem could conceivably have contributed to the high PM emissions observed.

Repairs to this truck included adjusting the acceleration smoke limiter and resetting three of the fuel pump sleeve lever adjustments. Other emissions-critical items such as the air filter, injector nozzles, rack stops, etc. were also checked, and found to be within specifications. These repairs

TABLE 4-4. REPAIR EFFECTS ON EMISSIONS, FUEL ECONOMY, AND POWER

Vehicle	Test No.	Periodic I/M Test Procedure: Full Power Lug-Down 100	90	80	70	60	3/4 Power Lug-Down 100	90	80	70	60	Acceleration Peak	SS	Snap Idle Peak	SS	Dynamometer Emissions Tests: Emissions (G/BHP-Hr) HC	CO	NOx	PM	Maximum Power (BHP)	Fuel Fuel Cons. (lb/BHP-HR)	Repair Action
PASADENA-02	1	10%	11%	14%	24%	39%	4%	3%	4%	7%	11%	82%	6%	72%	7%	0.78	3.49	7.60	0.94	148	0.641	Adj. smoke limiter &
PASADENA-02	2	3%	2%	2%	5%	11%	3%	2%	2%	3%	3%	28%	3%	27%	3%	0.86	3.17	5.30	0.79	155	0.611	governor. Reset sleeve
Percent Change		-70%	-82%	-86%	-79%	-72%	-25%	-33%	-50%	-57%	-73%	-66%	-50%	-63%	-57%	10%	-9%	-30%	-16%	5%	-5%	lever adj. to spec.
PASADENA-08	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	35%*	25%*	32%*	8%*	0.74	5.09	8.24	0.69	97	0.791	Reset timing, valves,
PASADENA-08	2	12%	13%	15%	16%	NA	2%	2%	2%	2%	NA	15%	1%	14%	2%	0.58	3.48	9.75	NA	109	0.690	and governor.
Percent Change		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-57%	-96%	-56%	-75%	-22%	-32%	18%	NA	12%	-13%	
LA USPS-05	1	7%	7%	7%	8%	15%	3%	3%	3%	4%	10%	50%	5%	66%	6%	0.27	1.53	6.18	0.44	306	0.444	Reset smoke limiter(?)
LA USPS-05	2	3%	3%	3%	4%	9%	2%	2%	2%	2%	4%	32%	3%	46%	3%	0.40	1.50	6.36	0.50	291	0.454	
Percent Change		-57%	-57%	-57%	-50%	-40%	-33%	-33%	-33%	-50%	-60%	-36%	-40%	-30%	-50%	48%	-2%	3%	14%	-5%	2%	
CALTRANS-03	1	1%	1%	1%	1%	NA	1%	1%	1%	2%	NA	32%	3%	33%	4%	0.81	1.95	4.80	0.49	175	0.576	Replace 5 bad nozzles.
CALTRANS-03	2	1%	2%	3%	6%	NA	2%	2%	2%	4%	NA	40%	2%	47%	1%	0.87	2.20	3.99	0.40	160	0.587	Reset valve lash.
Percent Change		0%	100%	200%	500%	NA	100%	100%	100%	100%	NA	25%	-33%	42%	-75%	7%	13%	-17%	-18%	-9%	2%	
LA GMC-03	1	14%	26%	24%	22%	34%	4%	4%	4%	5%	5%	98%	10%	100%	12%	1.13	4.87	10.86	0.72	281	0.522	Replace camshaft and fuel
LA GMC-03	2	8%	6%	5%	6%	4%	3%	2%	2%	3%	2%	37%	6%	52%	5%	0.37	3.93	13.18	0.45	286	0.517	pump. In-frame rebuild.
Percent Change		-43%	-77%	-79%	-73%	-88%	-25%	-50%	-50%	-40%	-60%	-62%	-40%	-48%	-58%	-67%	-19%	21%	-37%	2%	-1%	
LA GMC-08	1	2%	2%	5%	9%	NA	0%	3%	3%	6%	NA	80%	4%	15%	5%	0.77	3.34	9.21	0.36	264	0.494	Set valve lash, timing,
LA GMC-08	2	0%	0%	1%	2%	NA	0%	0%	0%	1%	NA	32%	3%	7%	3%	0.72	2.08	10.92	0.30	266	0.476	governor and racks to spe
Percent Change		-100%	-100%	-80%	-78%	NA	0%	-100%	-100%	-83%	NA	-60%	-25%	-53%	-40%	-6%	-38%	19%	-17%	1%	-4%	Adjust throttle delay.

* From ROC, PIMT smoke data unavailable.

dramatically reduced both transient and steady-state smoke, and improved fuel consumption somewhat as well. Particulate and HC emissions remained high, however, although NO_x was decreased significantly. The sharp reduction in NO_x emissions, together with the lower-than expected drop in PM and slightly increased HC suggests that the repairs to the fuel pump may have affected the injection timing.

Vehicle PASADENA-08--This truck was a moderately heavy smoker in the ROC, with very high stabilized emissions on the acceleration, stall idle, and snap idle tests. Unfortunately, PIMT smoke data for this truck are not available. Road-specific particulate, HC, and NO_x values were also moderately high, and road-specific fuel consumption was extremely high. Again, these high road-specific values may be at least partly due to an inefficient driveline, resulting in less engine power being transmitted to the wheels.

Repairs to this truck consisted of the routine tune-up procedure for DDA engines. This includes checking and resetting the injector timing, valve timing, rack settings, and governor. The injector timing was found to be retarded, and the governor setting was also off. The result of these repairs was a 12% increase in power and a 13% reduction in fuel consumption, along with dramatically lower smoke emissions. NO_x emissions were increased 18% by the advanced timing, however. Particulate emissions measurements for the post-repair test were not available, but the reduction in smoke suggests that they would have been lower as well.

Vehicle LA USPS-05--This truck had a Mack engine with air-to-air intercooling. It displayed moderate smoke emissions in the acceleration and lug-down tests in the ROC screening, but higher acceleration smoke in the PIMT. Overall emissions were fairly low, however. During testing, it was also observed that this vehicle (nominally rated, according to our information, at 285 engine horsepower) was apparently delivering 309 horsepower to the dynamometer rolls. This suggested that the fuel setting might have been "turned up" to increase power output.

This truck was returned to the USPS for repairs, which apparently involved resetting the smoke puff limiter and possibly the fuel pump. These greatly reduced the transient and steady-state smoke observed. Despite the reduction in smoke, the NO_x, particulate, HC, and fuel consumption measurements for this truck were all higher on the second test than on the first. These results are difficult to explain in terms of normal engine behavior. One possible explanation involves the air-to-air intercooler. The air flow rate past this heat exchanger is obviously critical to its performance. The measured results could be explained if the air flowrate (and thus the intercooler effectiveness) during the second test were significantly lower than during the first. Another possibility is experimental error—this vehicle was the first one successfully tested, and this may have affected the results. It is also notable that the smoke measurements for the first test were taken several days before the mass emissions measurements, which might also have affected the relationship between them.

Vehicle CALTRANS-03--This dump truck exhibited moderately high smoke opacities in all three test modes during the screening test. The smoke levels measured on the PIMT were somewhat lower, however, and would have resulted in a marginal "Pass" for all modes. The emissions test data indicated high HC and moderately high particulate, however. The HSLD personnel involved commented that the truck appeared to have "cleaned up" some on the dynamometer, and--significantly--the smoke opacity measurements for this truck were taken after the dynamometer emissions test. As discussed later in Section Five, the prolonged high-power operation during the emissions test could have affected the subsequent smoke opacity measurements.

A diagnostic examination of this truck indicated that five of the six fuel injection nozzles were malfunctioning in some way--spray patterns were off on two, one had a plugged hole, and two were dribbling. These problems were likely due to deposits formed on the injector nozzles. All six injectors were replaced. In addition, the valve lash on most of the intake and exhaust valves was excessive, and was reset to specifications. The smoke puff limiter apparently was not checked. The results, as shown in Table 4-4, were an increase in smoke in nearly all modes, but a moderate decrease in both particulate and NO_x emissions, and an increase in HC emissions and fuel consumption.

These data are hard to understand--replacing five bad nozzles should have decreased fuel consumption, particulate, and especially HC emissions substantially, while increasing NO_x somewhat. The very low NO_x emissions measured in the second test suggest one explanation. If the injection timing (already retarded to comply with California emission standards) had become even more retarded in the process of replacing the injectors, this could explain the observed changes.

Vehicle LA GMC-03--This truck-tractor was identified as a gross emitter during the screening tests. The subsequent emissions testing confirmed that HC, NO_x, and PM emissions were all quite high, although the NO_x emissions were not out of line with the standards, considering the truck's age. Subsequent diagnosis indicated that the injector camshaft lobe for one cylinder was bad, resulting in poor fuel injection in that cylinder. The governor and smoke puff limiter were also misset, and the injectors needed to be replaced. The entire engine was also worn. This engine was given a complete in-frame rebuild, with a new camshaft, liners, pistons, injectors, fuel pump, and other major components, and all systems were reset to specifications. As a result, smoke, particulate, and HC emissions were reduced dramatically, but NO_x emissions increased somewhat--as would be expected, given the higher compression pressures resulting from the new rings and liners. Power and fuel consumption were also improved by the rebuild.

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Vehicle LA GMC-08--This tractor was also identified as a gross emitter during the screening process. Smoke emissions during the PIMT were considerably lower, however, prompting comments that the engine had "cleaned up" on the dynamometer. At least part of this "cleaning up" was probably due to transient effects--the acceleration smoke opacity trace for this truck shows a rather broad peak, and it appears that the limited acceleration room at the GMC dealership was insufficient to allow it to stabilize. In contrast to its visually "smoky" appearance, the steady-state particulate emissions measured for this truck were quite moderate. The HC emissions, while higher than many of the other trucks tested, were not unusually high for this two-stroke engine, and the NO_x emissions were in line with the applicable standards at the time it was built. These steady-state emissions values are probably deceiving, however--given the slow response and extremely high transient smoke opacity, it is likely that this truck would have showed up as a gross emitter in a transient emissions test.

The repairs to this truck consisted of a "tune-up"--checking and adjusting the injector timing, valve lash, injector rack settings, governor, and throttle delay. This resulted in a dramatic reduction in transient smoke, and moderate reductions in steady-state smoke, particulate emissions, and fuel consumption. NO_x emissions were increased somewhat, presumably as a result of advancing the injector timing to specifications.

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5.0 ANALYSIS OF THE TEST DATA

This section presents our statistical analysis of the data generated by the validation testing program. This analysis addressed a number of specific issues and questions. These questions, listed in order of their occurrence within the test program, were as follows.

- How do visual smoke opacity estimates compare to opacity values measured with an opacimeter?
- How do the results of the ROC compare with those of the PIMT?
- How well do smoke opacity values correlate with particulate emissions?
- Which smoke opacity tests are most effective in identifying high particulate and HC emitters, and how effective are they?
- How well can cycle composite NO_x and HC emissions be predicted from concentration data for individual modes? Are these relationship strong enough to identify excess emitters reliably?

Discussions and statistical analyses of each of these issues are presented in the subsections below.

5.1 Visual vs. Measured Smoke Opacity

Figures 5-1 through 5-7 contain cross plots comparing the smoke opacity measured with the opacimeter with the visual opacity estimate for each mode in the field screening. For each figure, the opacimeter measurement is plotted on the horizontal axis, and the visual estimate on the vertical axis. Each point represents the average of two back-to-back tests on the same vehicle. Dotted cross-lines indicating the failure criterion for that mode are also shown on each plot. For a point falling in the upper right quadrant

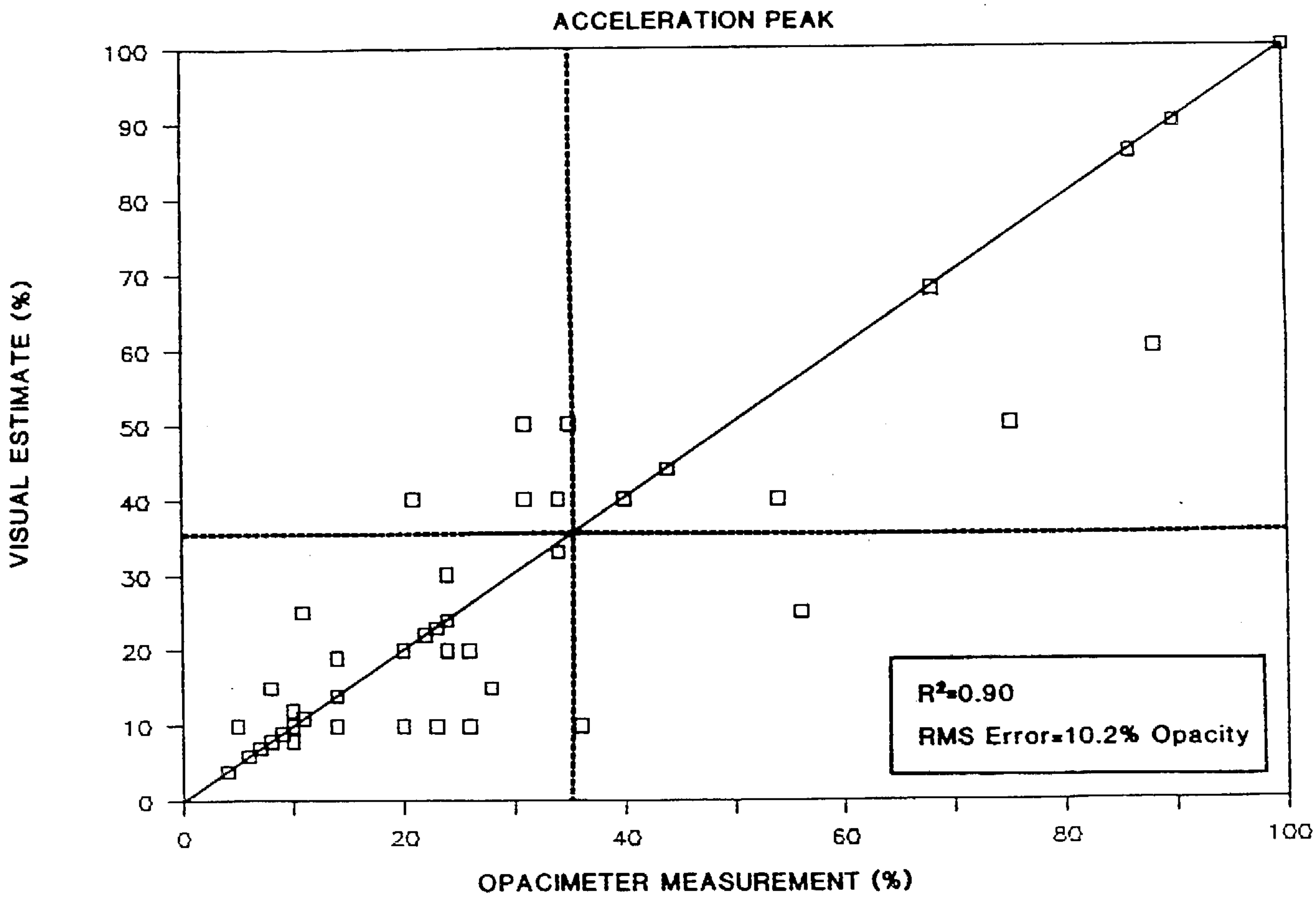

Figure 5-1. Visual vs. Measured Smoke Opacity (Acceleration Peak)

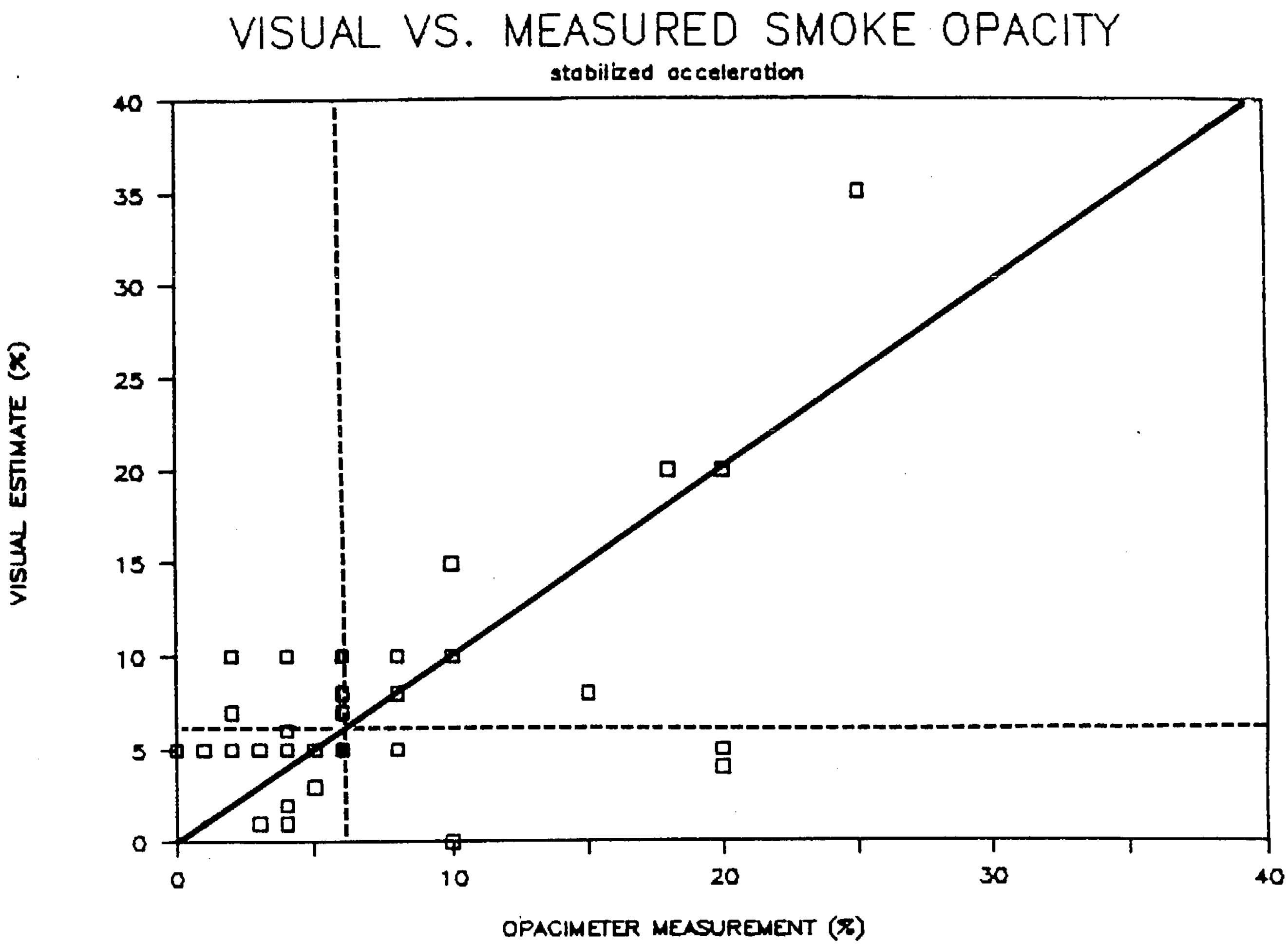

Figure 5-2. Visual vs. Measured Smoke Opacity (Stabilized Acceleration)

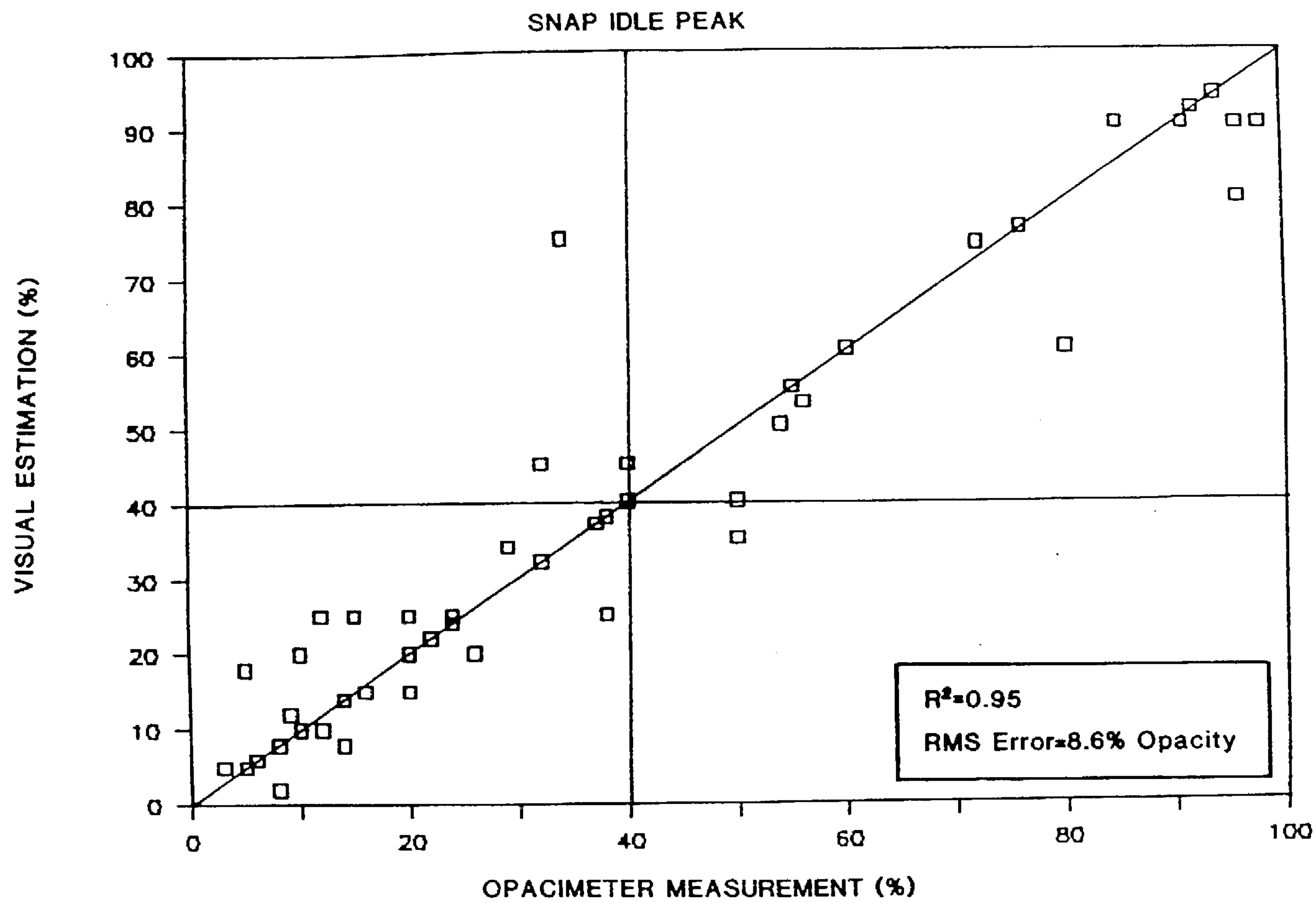

Figure 5-3. Measured vs. Visual Smoke Opacity (Snap Idle Peak Reading)

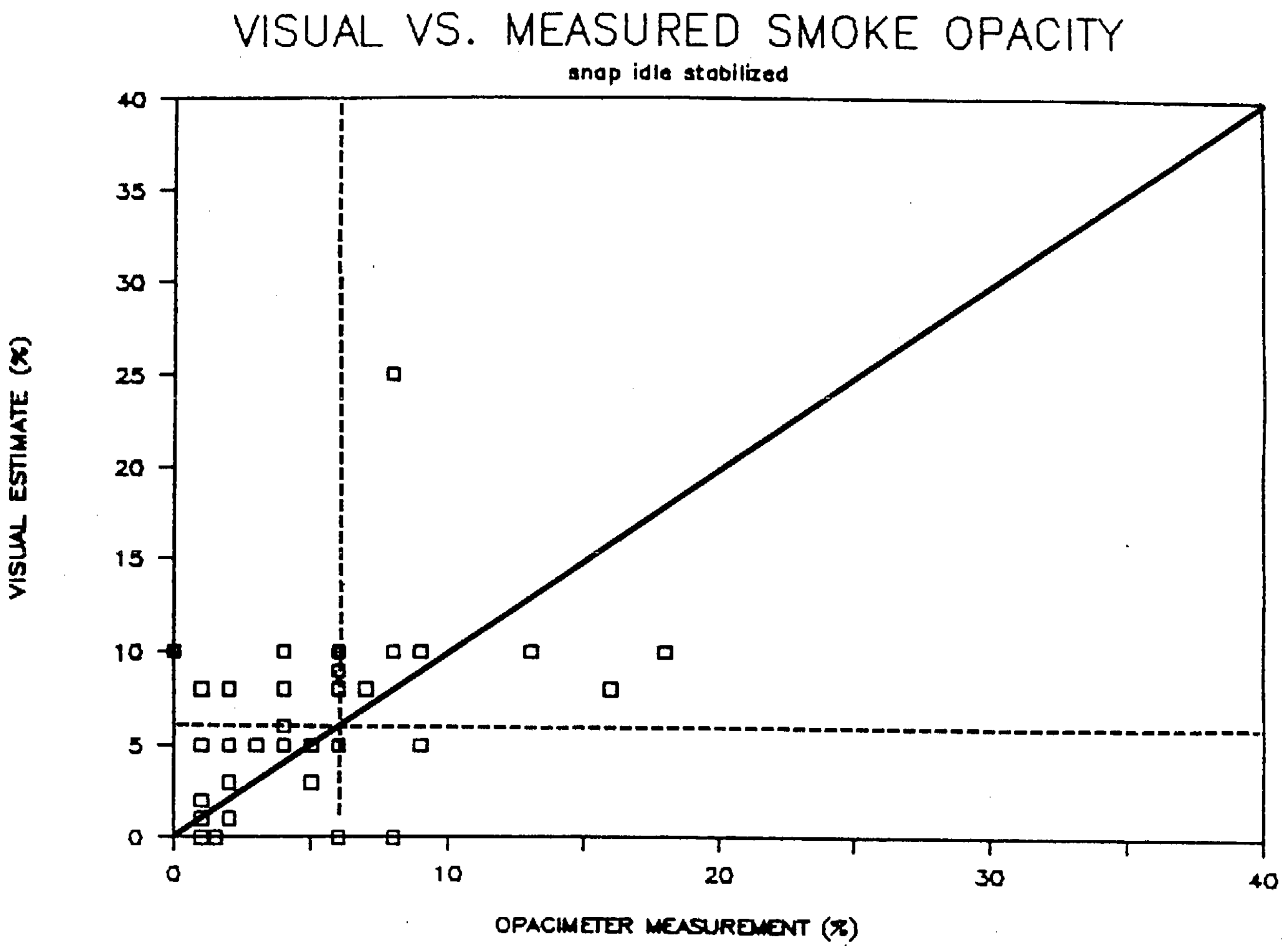

Figure 5-4. Visual vs. Measured Smoke Opacity (Snap Idle Stabilized)

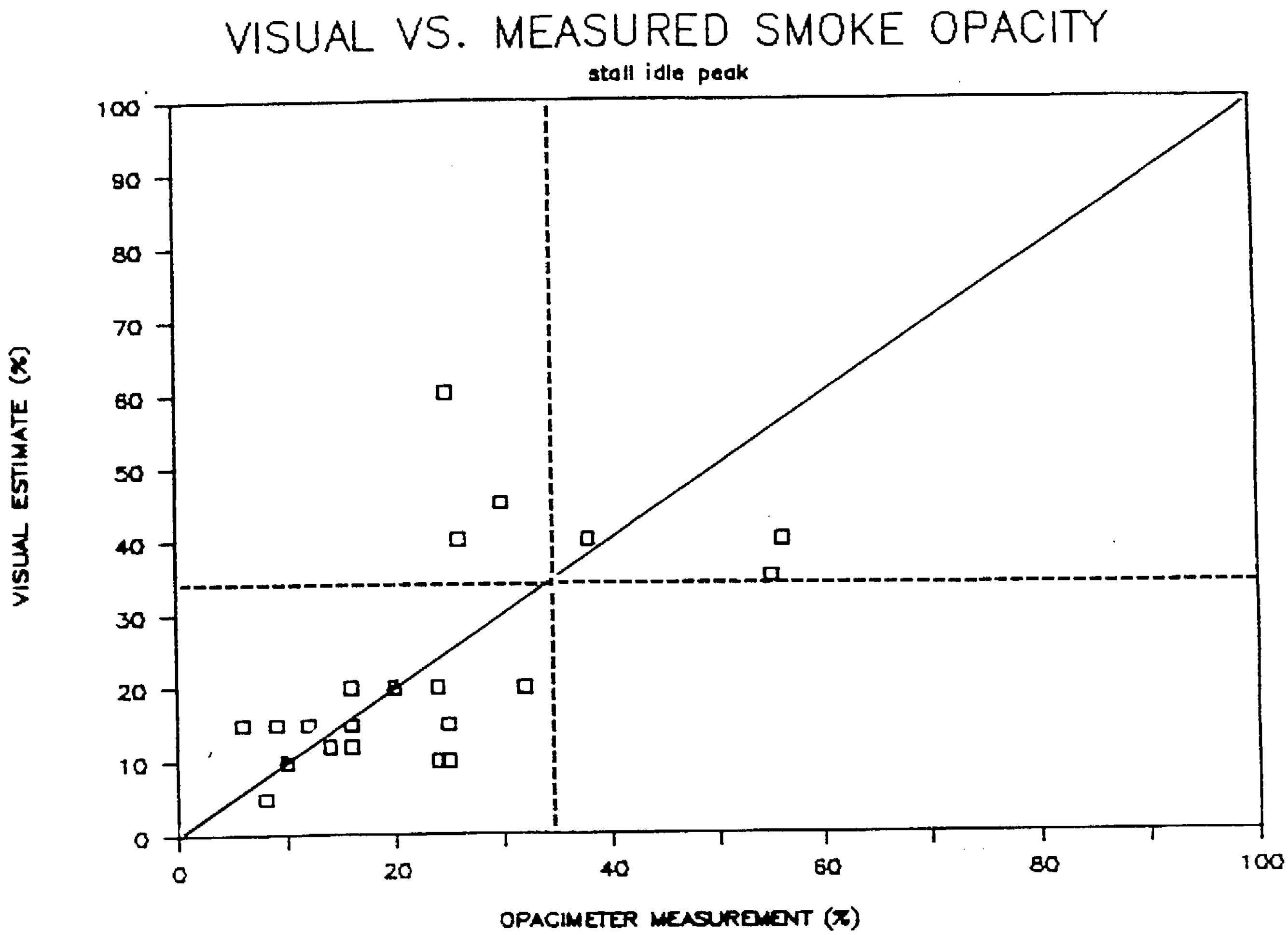

Figure 5-5. Visual vs. Measured Smoke Opacity (Stall Idle Peak)

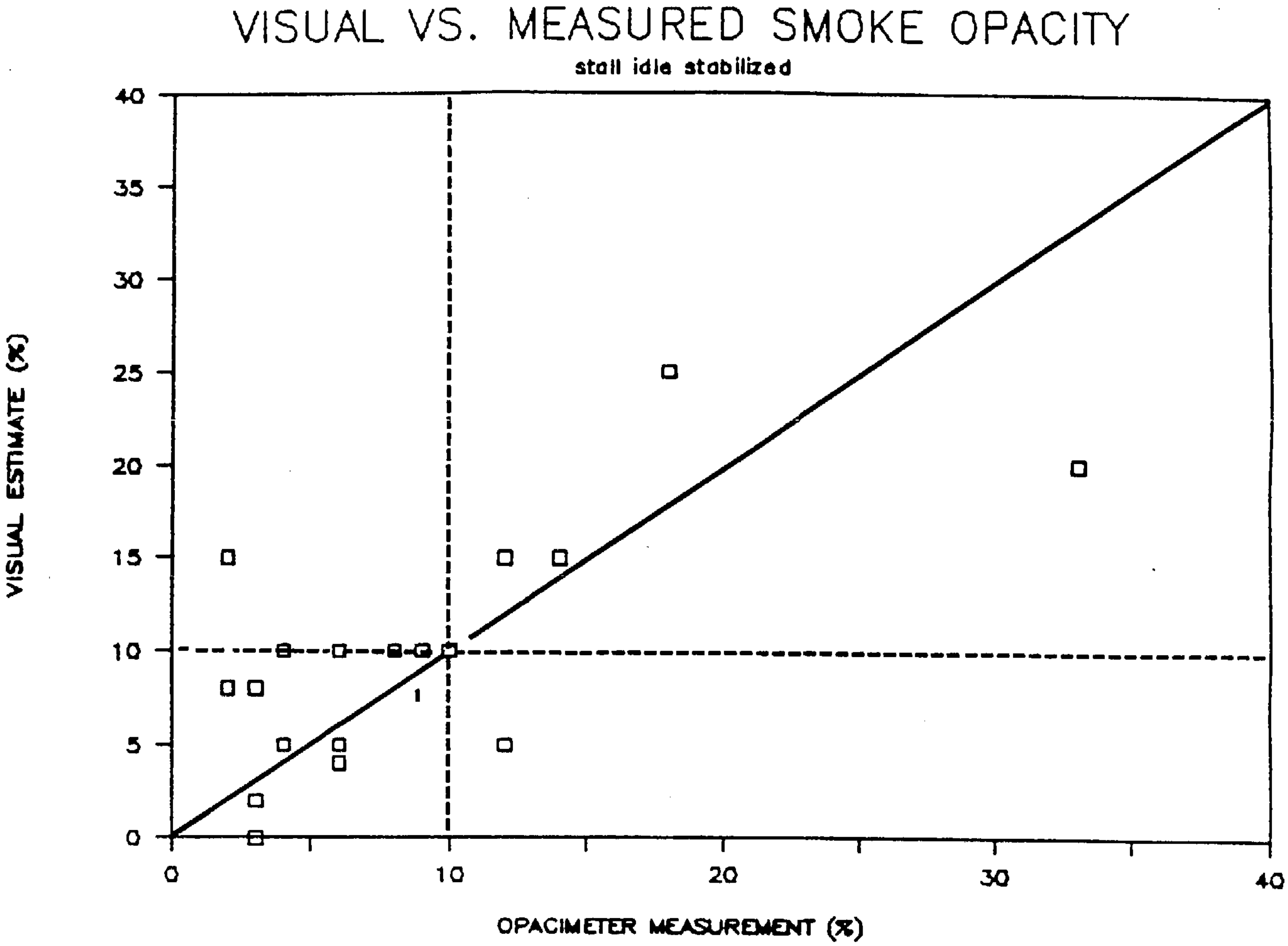

Figure 5-6. Visual vs. Measured Smoke Opacity (Stall Idle Stabilized)

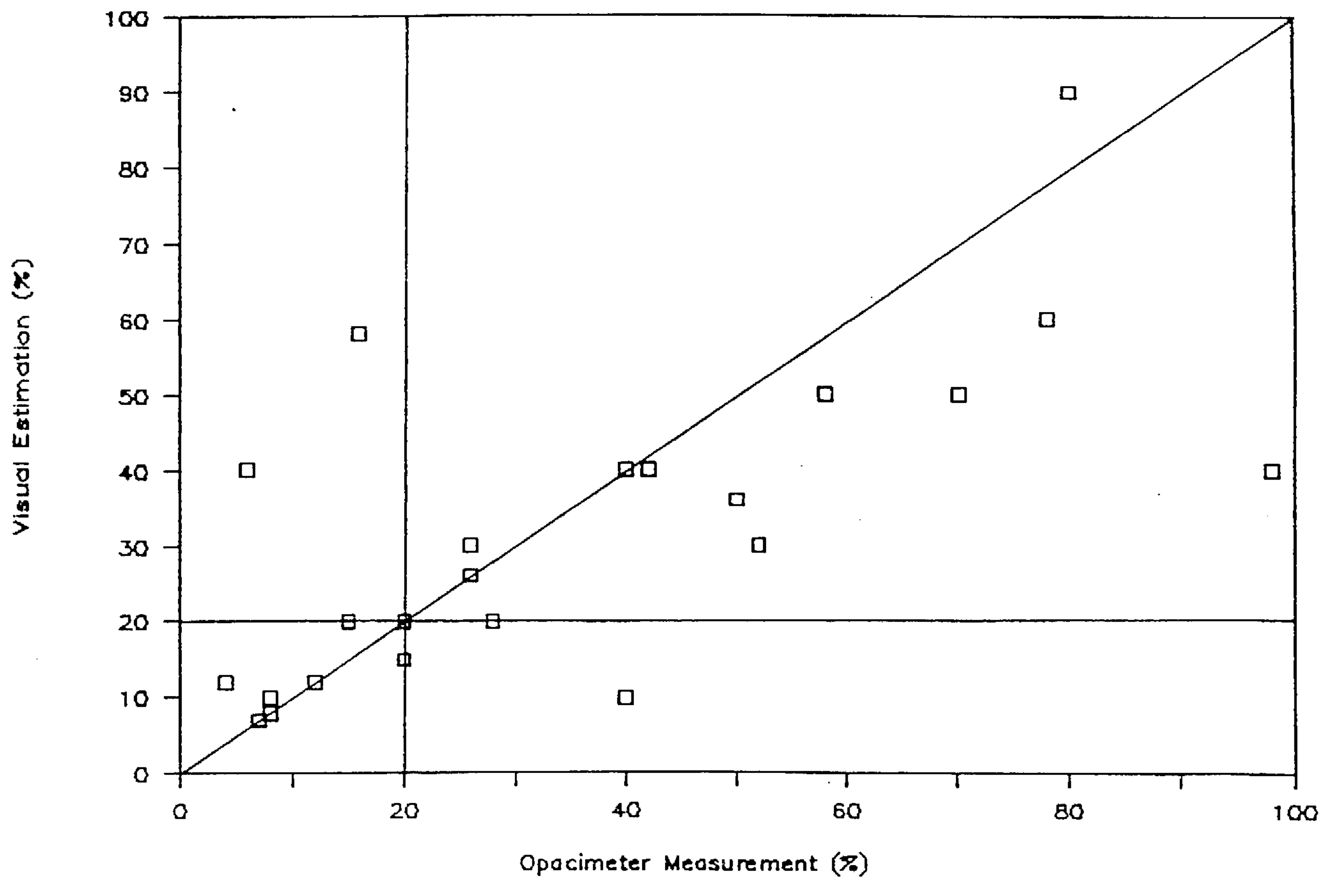

Figure 5-7. Measured vs. Visual Smoke Opacity (Lug-Down Peak Reading)

formed by these lines indicates that the vehicle would have failed an I/M test based on that criterion, whether the opacity was estimated visually or measured with the opacimeter. Similarly, a point in the lower left quadrant shows that the vehicle would have passed by either measurement. Points in the upper left and lower right quadrants indicate disagreement between the two methods--a vehicle passing by visual estimate but failing by opacimeter, or vice versa.

These data indicate a fair degree of correspondence between the visual opacity estimates and the opacimeter data in the moderate-to-high opacity range. This range is the one of greatest interest for smoke observation. It was much harder to estimate smoke opacities accurately in the lower opacity range, and a greater number of significant errors occurred. Relatively few of these errors were large enough to change the outcome of an I/M test, however, as the small populations in the upper left and lower right quadrants of the plots indicate. Visual estimates in the steady-state operating modes were much less reliable, due to the very low opacities measured in the steady-state modes.

The correspondence between visual and opacimeter readings is best for the snap idle and stall idle modes, in which the vehicle was standing still close to the observer. In the acceleration and lug-down modes, the motion of the vehicle and its greater distance from the observer reduced the accuracy of the estimate. Entrained dust also complicated the visual estimation for trucks with exhausts under or behind the vehicle. Some of the differences between visual and opacimeter reading in these modes may have stemmed from uncertainty on the part of the observer as to which mode was which, since the lug-down immediately followed the acceleration. Finally, the problems with the lug-down test--discussed in Section 3.3--contributed significantly to the comparatively poor correspondence between measurements in this mode.

These data are especially significant because the ARB employee making the visual estimates had not been trained in smoke opacity estimation (unlike the observer in the visual smoke survey, who was an ARB-certified Smoke Reader). This indicates that someone with no previous formal training can quickly learn to distinguish smoke opacity levels with reasonable accuracy. This could simplify the implementation of the ROC, since an officer could distinguish passing from failing levels by eye in most cases. Marginal or protested cases could then be confirmed using an opacimeter.

5.2 Comparison of ROC and PIMT Results

The PIMT opacity tests and the ROC involve similar operating conditions, and are intended to generate similar results. It is instructive, therefore, to examine the degree of correspondence between these similar tests. Figures 5-8 through 5-12 plot the PIMT opacity measurements for acceleration (peak and stabilized), snap idle (peak and stabilized), and lug-down modes against the corresponding values for the ROC. The crossed vertical and horizontal lines in each plot mark the failure criteria for each test mode, developed in Section Two. A point plotted in the lower left quadrant formed by these lines indicates that the truck would have passed both the ROC and PIMT tests for that mode; one in the upper right quadrant indicates that it would have failed both tests.

As these plots indicate, there is a fair degree of correspondence between the two sets of measurements in the acceleration and snap idle tests. With some exceptions, vehicles showing high opacity values in the ROC also showed high values in the PIMT. The correspondence is considerably better for the acceleration than for the snap idle, which may reflect a greater degree of repeatability with the acceleration test.

Some of the discrepancies observed in these measurements are probably due to changes in engine condition between the time they were tested during the screening test and the time they were brought into HSLD. The laboratory personnel also observed that some of the trucks tested appeared to "clean up" when run on the dynamometer. Especially in the early tests, this involved running for considerable periods at or near full power. This prolonged high-

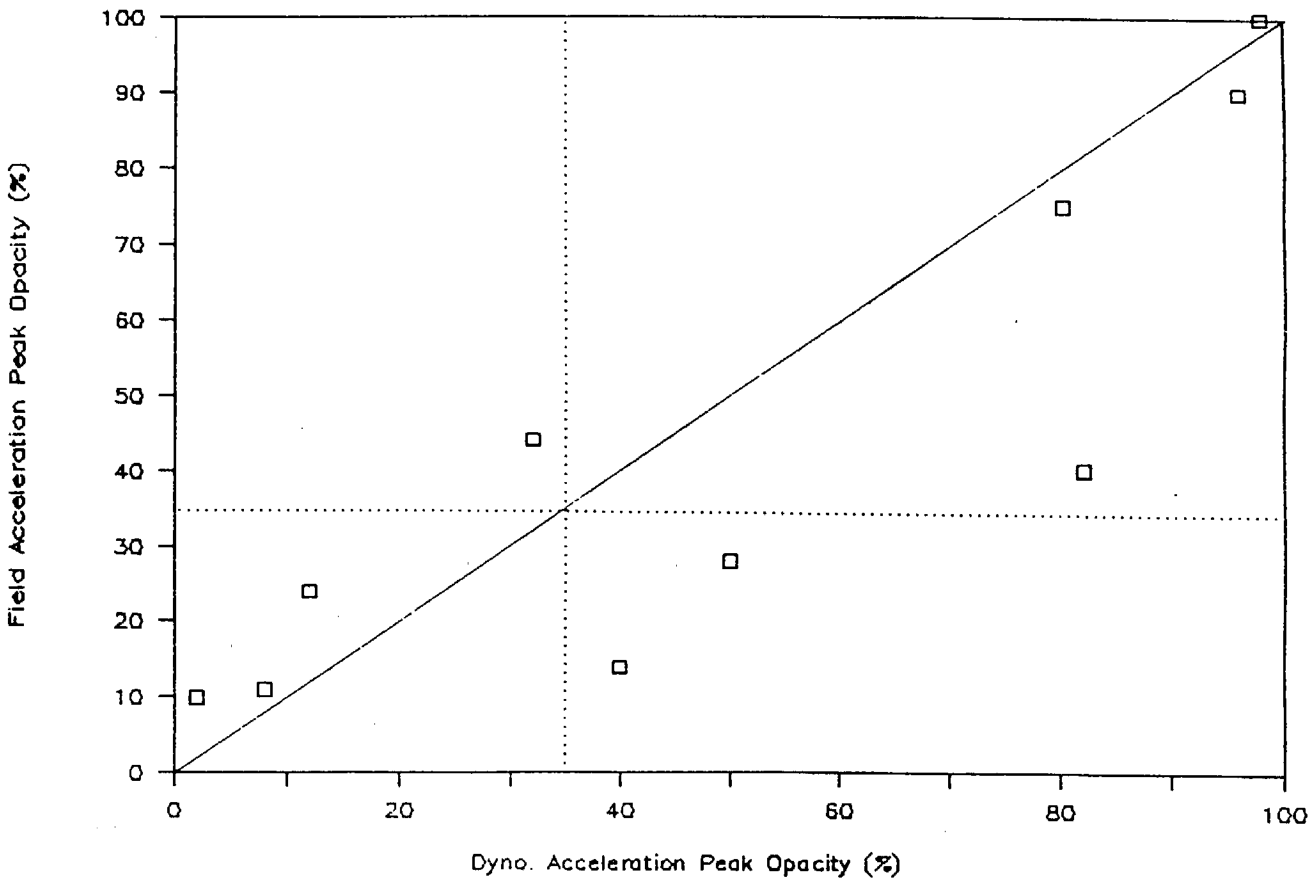

Figure 5-8. Acceleration Peak Opacity Values from Dynamometer Tests vs. Field Screening

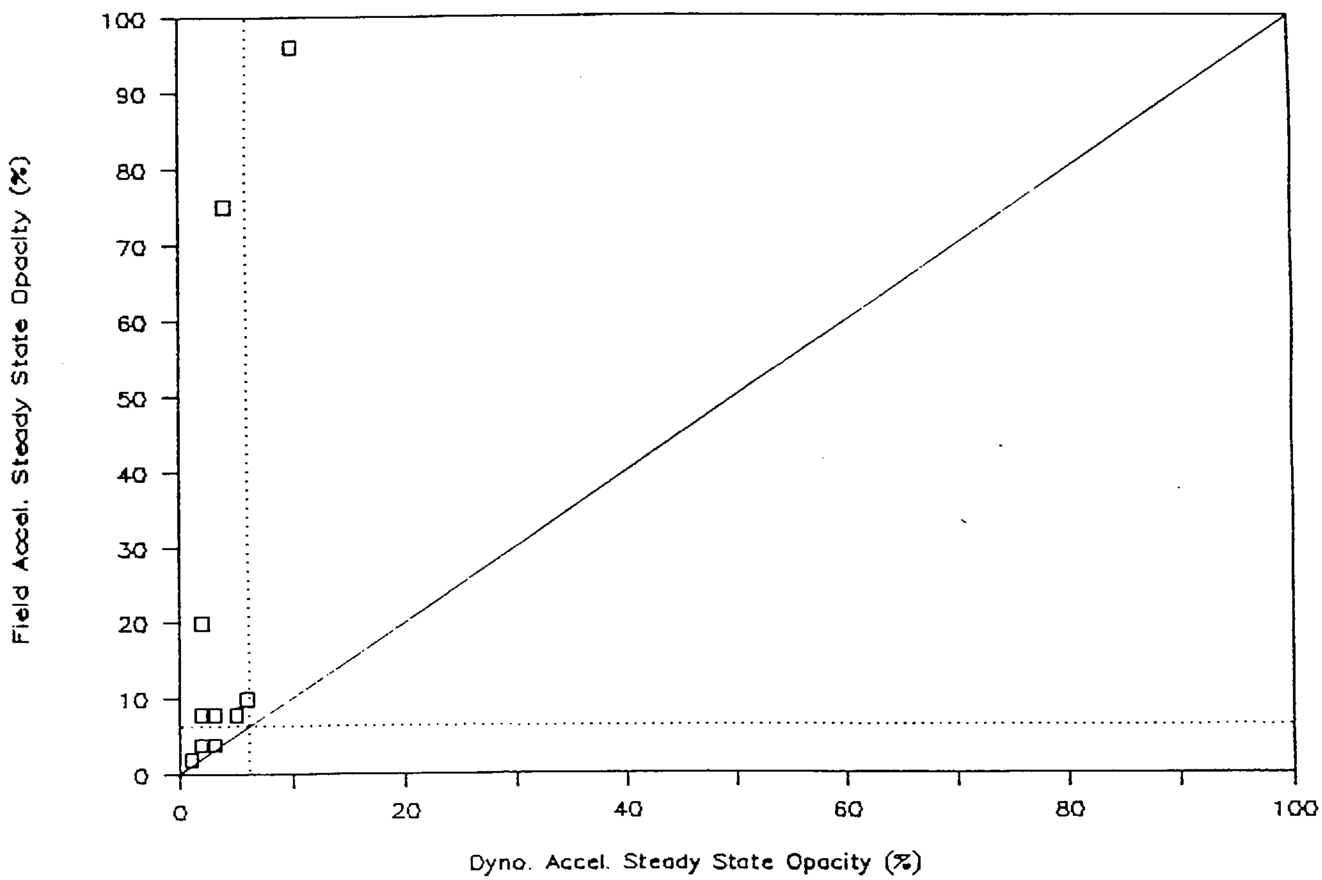

Figure 5-9. Acceleration S.S. Opacity Values from Dynamometer Tests vs. Field Screening

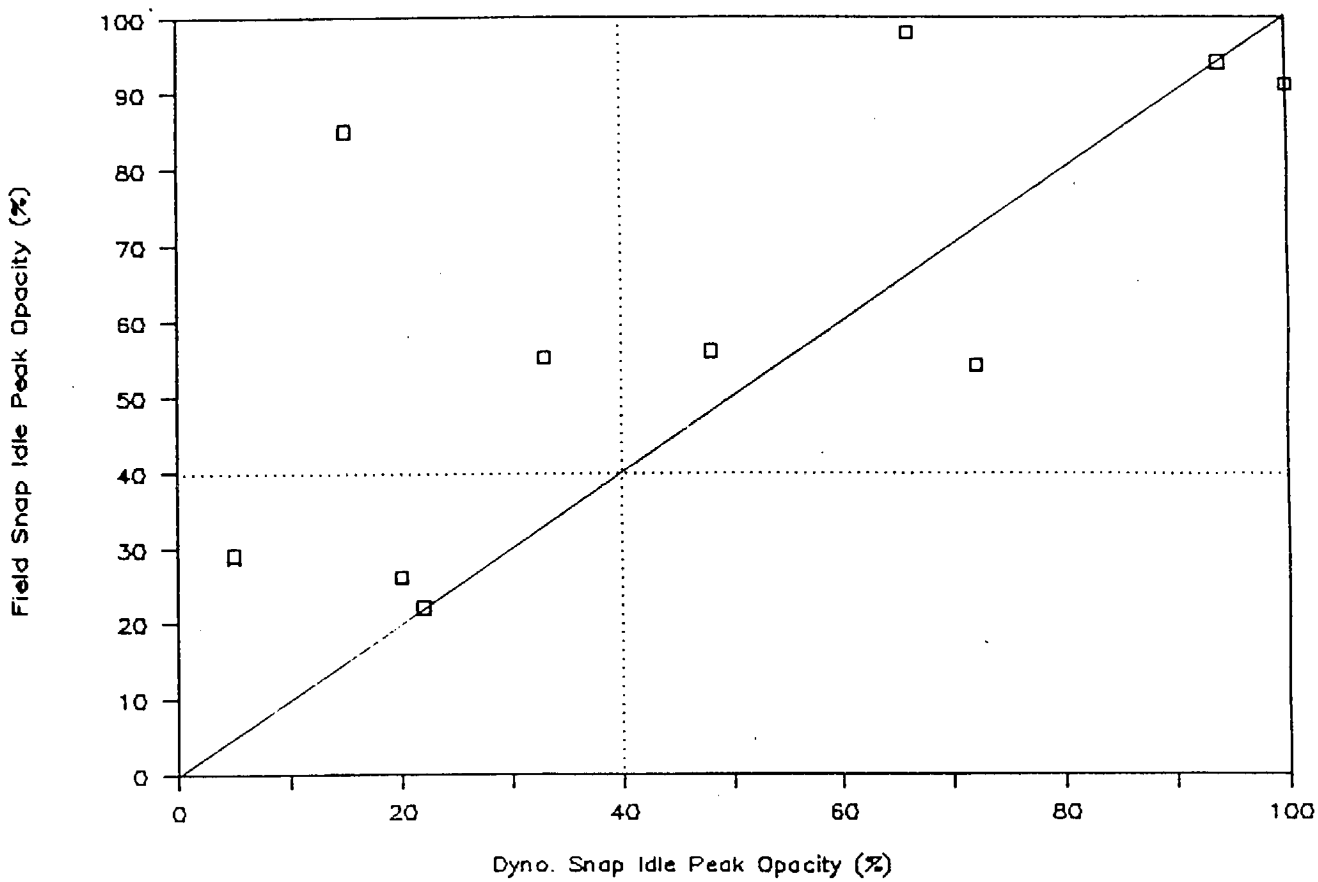

Figure 5-10. Snap Idle Peak Opacity Values from Dynamometer Tests vs. Field Screening

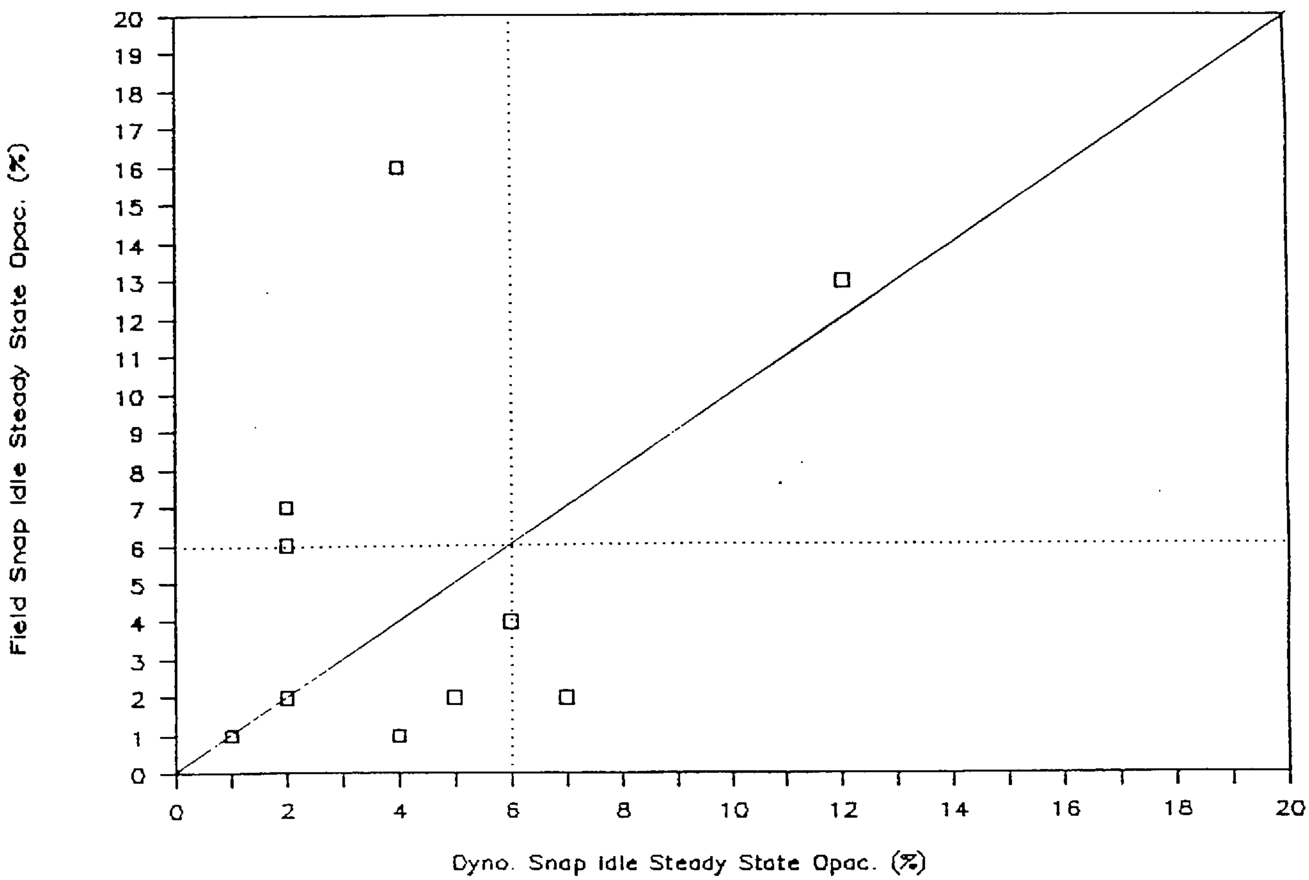

Figure 5-11. Snap Idle S.S. Opacity Values from Dynamometer Tests vs. Field Screening

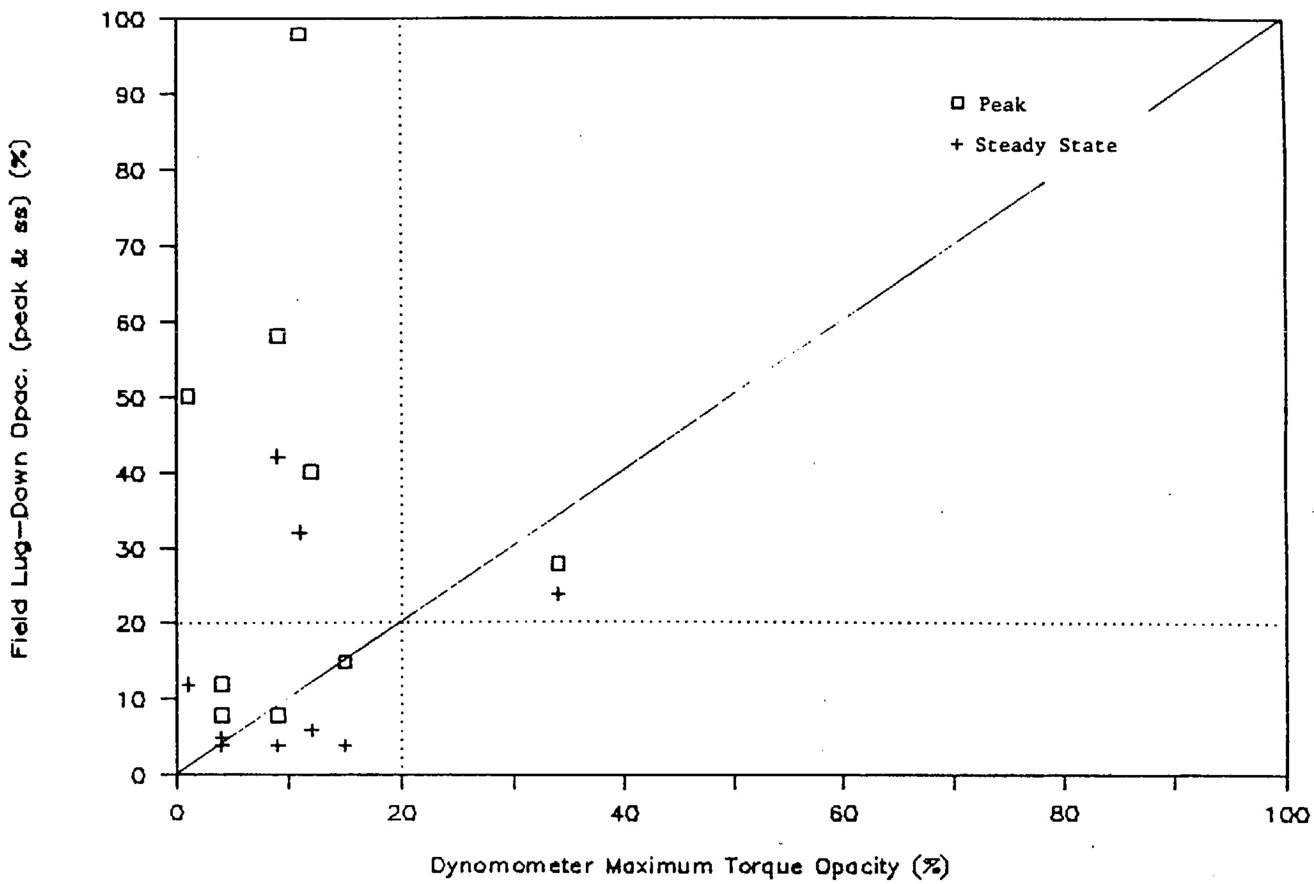

Figure 5-12. Lug-Down Opacity Values from Dynamometer Tests vs. Field Screening

power operation could have burned off any deposits on the injector spray holes (due to poor fuel quality, for instance), and thus reduced the apparent smokiness on the PIMT.

Figure 5-9 shows two very high readings for stabilized acceleration smoke in the field test which were not duplicated in the laboratory measurements. These high readings were due to a combination of slow turbocharger response and limited room for the road acceleration testing. Due to the limited room, it was necessary to brake before the acceleration response had stabilized. The dynamometer acceleration measurement at HSLD was not affected by lack of room, and thus measured the true stabilized opacity. A milder version of this problem may also have affected some other measurements, resulting in stabilized opacity values in the ROC which were somewhat higher than those measured in the PIMT.

In contrast to the acceleration and stall idle data, the lug-down data shown in Figure 5-12 show very poor correspondence between the ROC data (measured by lugging the vehicle against its service brake) and the dynamometer data from the PIMT. This is considered to be due to the repeatability problems with the ROC lug-down test. These problems were discussed in Section 3.3. Based on these results, the ROC lug-down test does not appear acceptable for enforcement purposes.

5.3 Correlation of Smoke Opacity With Particulate Emissions

Correlation and multiple linear regression analyses were performed, comparing the smoke opacity data from the PIMT with cycle-composite particulate emissions from the chassis 13-mode cycle. Perfect correlation was not anticipated, as it was known that some problems (e.g. misset smoke limiters) can lead to very high peak smoke opacities, while having only a moderate effect on cycle-composite emissions (indeed, the acceleration smoke limiter should have had <u>no</u> effect on PM emissions in these steady-state tests).

Correlation analyses indicated that the best predictors of 13-mode PM emissions were the smoke opacity at the maximum torque point (lug-down smoke), 75 percent power at rated speed (road load smoke), and 100 percent power at rated speed (maximum power smoke). Surprisingly (given the steady-state test cycle) acceleration peak smoke also turned out to correlate reasonably well with PM emissions. Subsequently, regression analyses were carried out using lug-down, road-load, and acceleration peak smoke opacities. The results for the lug-down and acceleration peak regressions are plotted in Figures 5-13 and 5-14.

The best one-variable model for PM emissions was the one having lug-down smoke opacity (O_{ld}) as the independent variable. R^2 for this model was calculated as 0.60, indicating only fair correlation. The results of this model are plotted as the dashed line in Figure 5-13.

Examination of Figure 5-13 shows that the visual fit of the data could be substantially improved if the two points marked PASADENA-02 were excluded. These points represent before and after-repairs measurements on one truck. This truck had the only automatic transmission in the group, and was later found to be suffering from overheating, due to the installation of an incorrect cylinder head gasket. Either or both of these could have affected the correlation between smoke and PM emissions. However, repeating the regression without these two data points did not improve the statistical fit. This regression is shown as the solid line in Figure 5-13. Part of the reason for the poor fit is undoubtedly the limited range of PM emissions data in the remaining sample.

Figure 5-14 is a plot of acceleration peak smoke opacity (O_{acc}) vs. particulate emissions. As this figure shows, the correlation is rather poor--the best fit model has an R^2 value of only 0.19. This model is plotted as the dashed line in Figure 5-14. Again, the exclusion of data for truck PASADENA-02 had little effect on the quality of the fit. This regression is shown by the solid line in Figure 5-14. This poor correlation is not surprising, since several of the trucks exhibiting high transient smoke

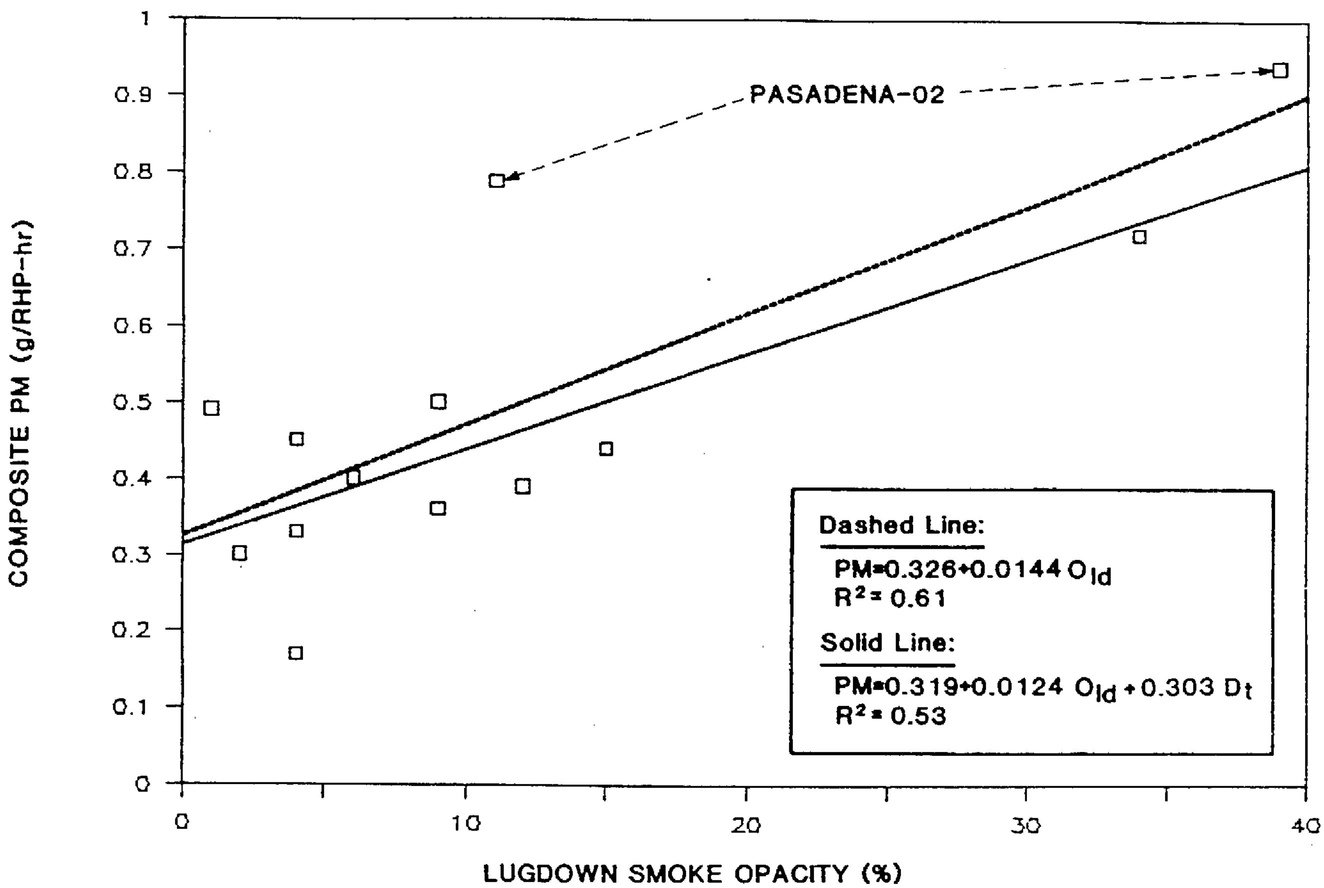

Figure 5-13. Particulate Emissions vs. Lug-Down Opacity

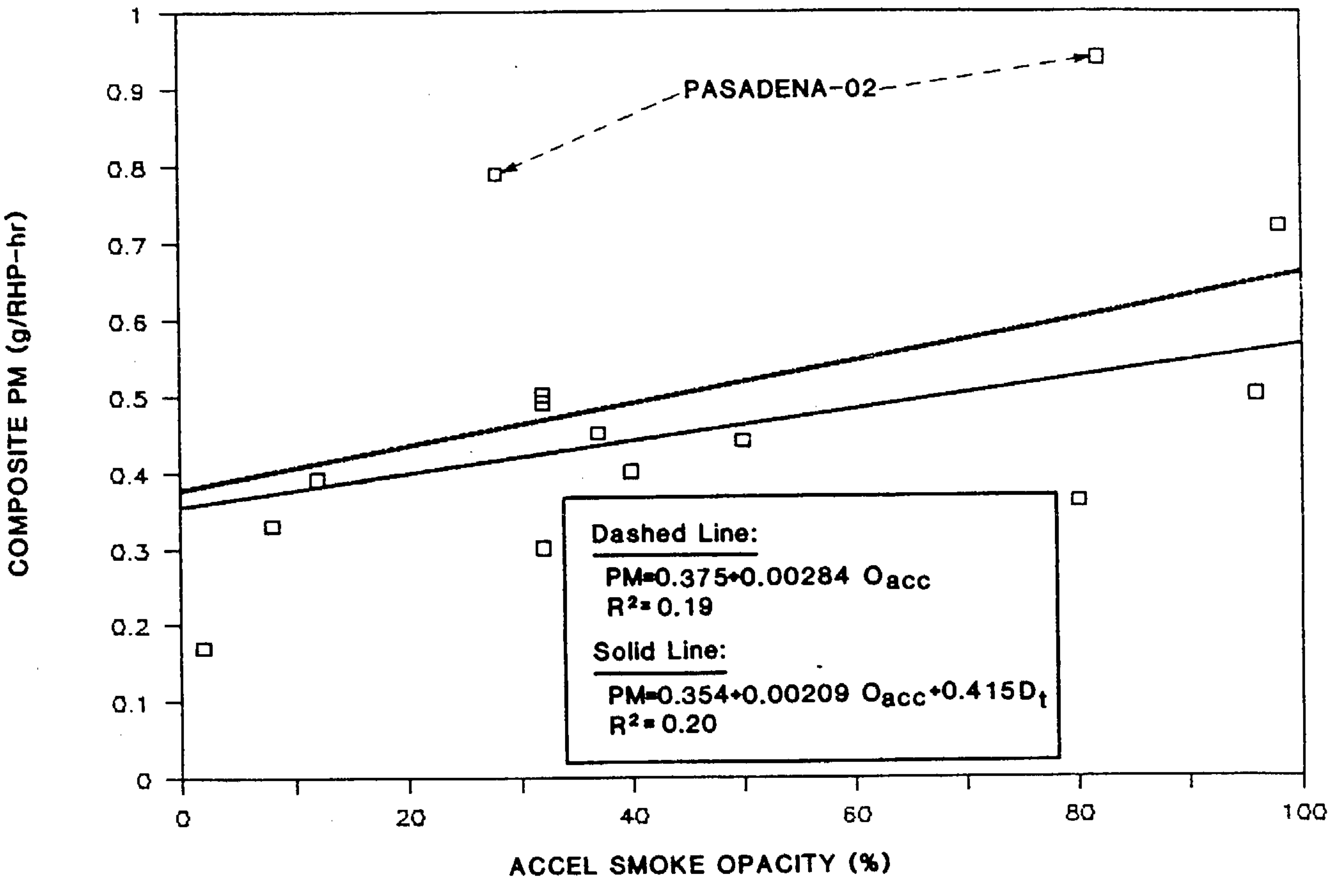

Figure 5-14. Particulate Emissions vs. Acceleration Peak Smoke Opacity

emissions during acceleration had rather low steady-state emissions, and these are what would have been measured in the steady-state emissions tests performed. Emissions from these trucks would probably have been much higher if they had been measured using a transient emissions test cycle.

5.4 Effectiveness of Smoke Opacity Tests in Identifying Excess Emitters

Table 5-1 shows the results of a pass/fail analysis of the 14 tests performed in Task 4 for which both particulate and smoke measurements were available. This table shows the number of "true positive", "false positive", "true negative" and "false negative" results generated by each test mode, using the failure criteria developed in Section Two. A "true positive" is a high-emitting vehicle which fails the smoke opacity test; a "false positive" is a low-emitting vehicle which fails. Similarly, a "true negative" is a low-emitting vehicle which passes the test; and a "false negative" is a high-emitting vehicle which passes. False positives and false negatives correspond to errors of commission and errors of omission, respectively.

For this analysis, "high-emitting" vehicles were defined as those having either PM or HC emissions in excess of 0.6 g/RHP-hr in the 13-mode emissions test. This HC value is roughly comparable to the old California HC limit of 0.5 g/BHP-hr, measured on the 13-mode cycle on an engine dynamometer. No comparable standard exists for particulate emissions, but the value of 0.6 g/RHP-hr is believed to lie well above the typical new engine emissions level on the 13-mode cycle.

Table 5-1 also shows the percentage of the total excess HC and PM emissions identified by each of the tests. Consistent with the definition of a "high emitter", "excess" emissions were also defined as those exceeding 0.6 g/RHP-hr for either HC or PM.

As Table 5-1 shows, several of the smoke opacity tests were equally effective in identifying high particulate emissions, but the acceleration peak

TABLE 5-1. EFFECTIVENESS OF SMOKE OPACITY TESTS IN IDENTIFYING HIGH EMITTERS

Test	Cutpoint (Opacity)	True Neg	False* Neg	False** Pos	True Pos	Total	Percentage of Excess Emissions Detected PM	HC
Accel Peak	35%	4	3	2	5	14	71%	67%
Accel Stabilized	6%	6	7	0	1	14	18%	29%
Snap Idle Peak	35%	3	4	3	4	14	71%	58%
Snap Idle Stabilized	10%	6	6	0	2	14	71%	39%
Lug-Down	20%	6	6	0	2	14	71%	39%
Road Load	5%	6	8	0	0	14	0%	0%

* Error of omission
** Error of commission

and snap idle peak were the most effective in identifying high HC emissions. The acceleration peak test also had the fewest false negatives of any of the tests. The two false positives (errors of commission) with the acceleration test should not really be considered as such, since each of the trucks in question exhibited offensively high transient smoke, even though its steady-state particulate emissions were low. As the purpose of these I/M tests is to reduce both excess emissions and occurrences of offensive smoke, identification of these trucks should not be considered an error of commission.

It was shown in the previous section that the combination of road-load opacity and acceleration peak opacity correlated better with PM emissions than did acceleration peak opacity alone. No vehicles in this dataset failed the original road load opacity criterion, however, so this test added nothing to the procedure's effectiveness. Using a more stringent criterion of 3% opacity in road load also did not increase the number of true positives beyond those identified by the acceleration test alone, and it increased the number of false positives by one. Thus, for this dataset, the addition of the road-load opacity measurement to the acceleration measurement provided no benefits.

As shown in Section Six, however, the road-load cruise opacity does identify some high-emitting vehicles which pass the acceleration smoke test (these are typically vehicles in which the acceleration smoke limiter has been adjusted to minimize transient smoke, but which are nevertheless significant emitters in steady-state operation). It is recommended, therefore, that this test mode be retained in the final PIMT. This would be especially desirable if the peak opacity cutpoint in the PIMT were set relatively high.

5.5 Correlation of Modal NO_x and HC Concentrations with Emissions

In Section Two, it was suggested that measurement of exhaust gas NO_x and HC concentrations in specific operating modes could be used to identify vehicles emitting excessive amounts of these pollutants. This approach is used in nearly all I/M programs for spark-ignition vehicles. A study by the Engine Manufacturers Association (Sienicki, 1982) also indicated that the average of the NO_x concentrations at high idle and at rated power correlated well with cycle-composite NO_x emissions for a wide range of engines.

In order to evaluate the effectiveness of this type of test for heavy-duty diesel vehicles, we calculated the correlation coefficients between pollutant concentrations in each of the 14 test modes and composite emissions calculated for the test cycle as a whole. Cycle-composite emissions were calculated in the same way as for the old Federal 13-mode test. These correlation coefficients are shown in Table 5-2. As this table indicates, the best correlations for both HC and NO_x were obtained for modes 4 and 5. The operating conditions for these modes are 50% and 75% power, respectively, at rated speed.

The fact that the best correlation was achieved at an intermediate power level suggested that an average of the values for two extreme power levels might give even better results. As Table 5-2 indicates, however, this was not the case for NO_x. For the NO_x dataset, the correlations obtained by averaging modes 6 and 2 together and modes 6 and 12 together were nearly equivalent, and were worse than the correlation with mode 4. For HC, however, these two averages did give a significantly better correlation than any of the individual modes. The operating conditions for modes 6, 2, and 12 are full power at rated speed, 2% power at rated speed, and 2% power at intermediate speed, respectively.

A linear regression analysis was carried out comparing the modal emissions concentrations to the cycle composite values. Again, the results of this analysis showed that the NO_x concentration in mode 4, alone, gave the best correlation with cycle composite NO_x. This relationship is shown in Table 5-2, and is plotted in Figure 5-15. Since cycle-composite NO_x for the old Federal 13-mode test is known to correlate well with NO_x in the Federal Transient Test, it is likely that the mode 4 NO_x concentration is a reasonable predictor of transient-test NO_x as well. This should be verified by additional research, however.

TABLE 5-2. CORRELATION OF MODAL NO_x AND HC CONCENTRATIONS WITH CYCLE COMPOSITE EMISSIONS

Mode	Speed	Load	NOx R^2	NOx Signif.*	HC R^2	HC Signif.*
1,7,13	Idle	0%	0.0006	1.0	0.327	0.201
2	Rated	2%	0.458	0.0645	0.529	0.029
3	Rated	25%	0.590	0.0129	0.561	0.019
4	Rated	50%	0.872	<0.0001	0.558	0.020
5	Rated	75%	0.850	<0.0001	0.621	0.008
6	Rated	100%	0.785	0.0002	0.579	0.015
8	Inter	100%	0.704	0.0016	0.541	0.025
9	Inter	75%	0.699	0.0018	0.490	0.046
10	Inter	50%	0.594	0.0120	0.343	0.177
11	Inter	25%	0.393	0.118	0.312	0.223
12	Inter	2%	0.522	0.032	0.465	0.060
14	Gov. Speed	0%	0.498	0.042	0.544	0.024
Average modes 6 and 2			0.823	<0.0001	0.717	0.0012
Average modes 6 and 12			0.837	<0.0001	0.727	0.0010

Linear Regression Analysis	R^2
$NO_{x\,(cycle)} = 0.636 + 0.0178\ NO_{x\,(Mode\ 4)}$	0.76
$HC_{(cycle)} = 0.150 + 0.0028\ HC_{(Mode\ 6)} + 0.00066\ HC_{(Mode\ 14)}$	0.73

* Probability of showing this correlation by random chance.

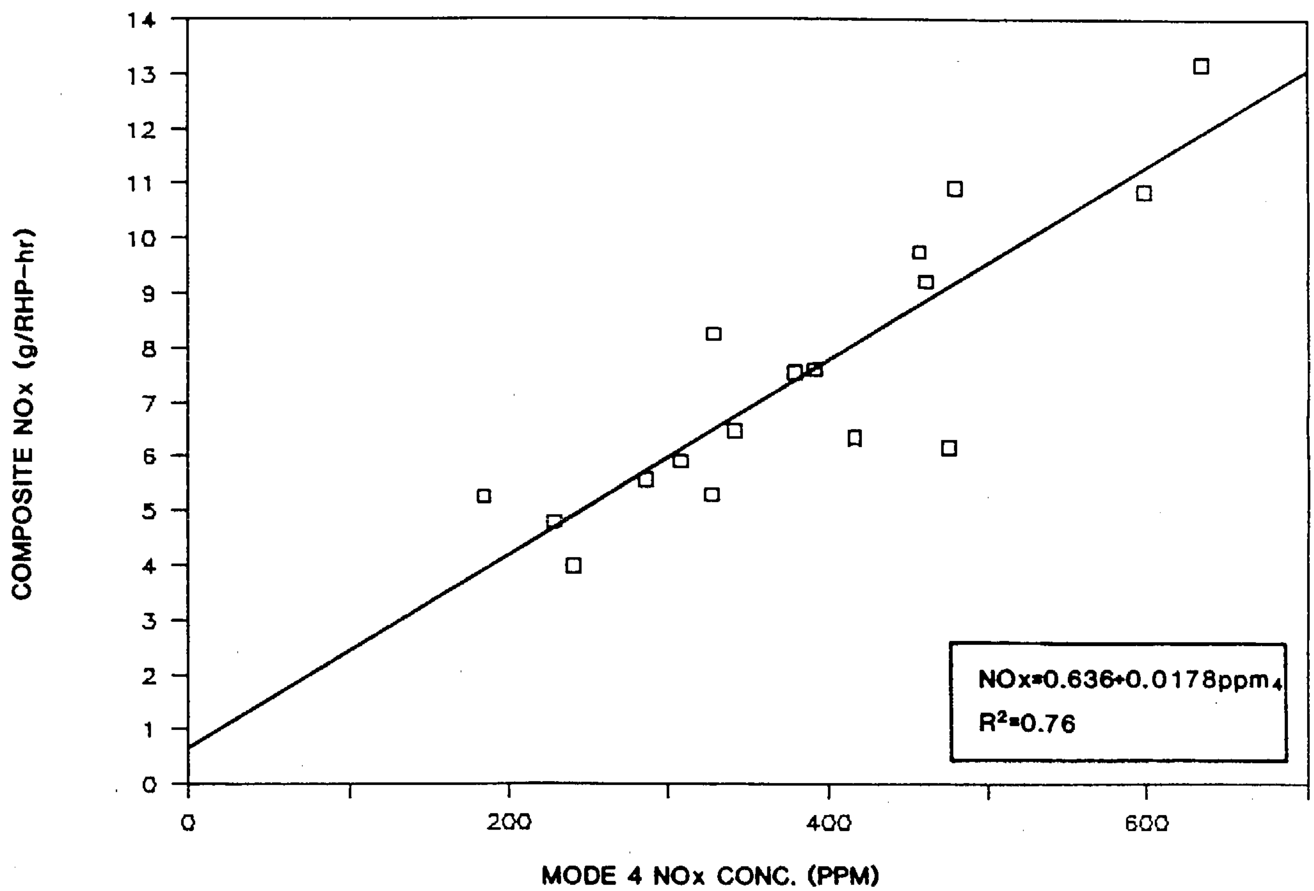

Figure 5-15. No_x Emissions vs. Mode 4 Concentrations

For HC emissions, the linear regression analysis indicated that a combination of HC concentrations in modes 6 and 14 gave the best prediction of cycle-composite HC emissions. This relationship is also shown in Table 5-2. A cross plot of actual HC emissions vs. emissions predicted by this equation is given in Figure 5-16.

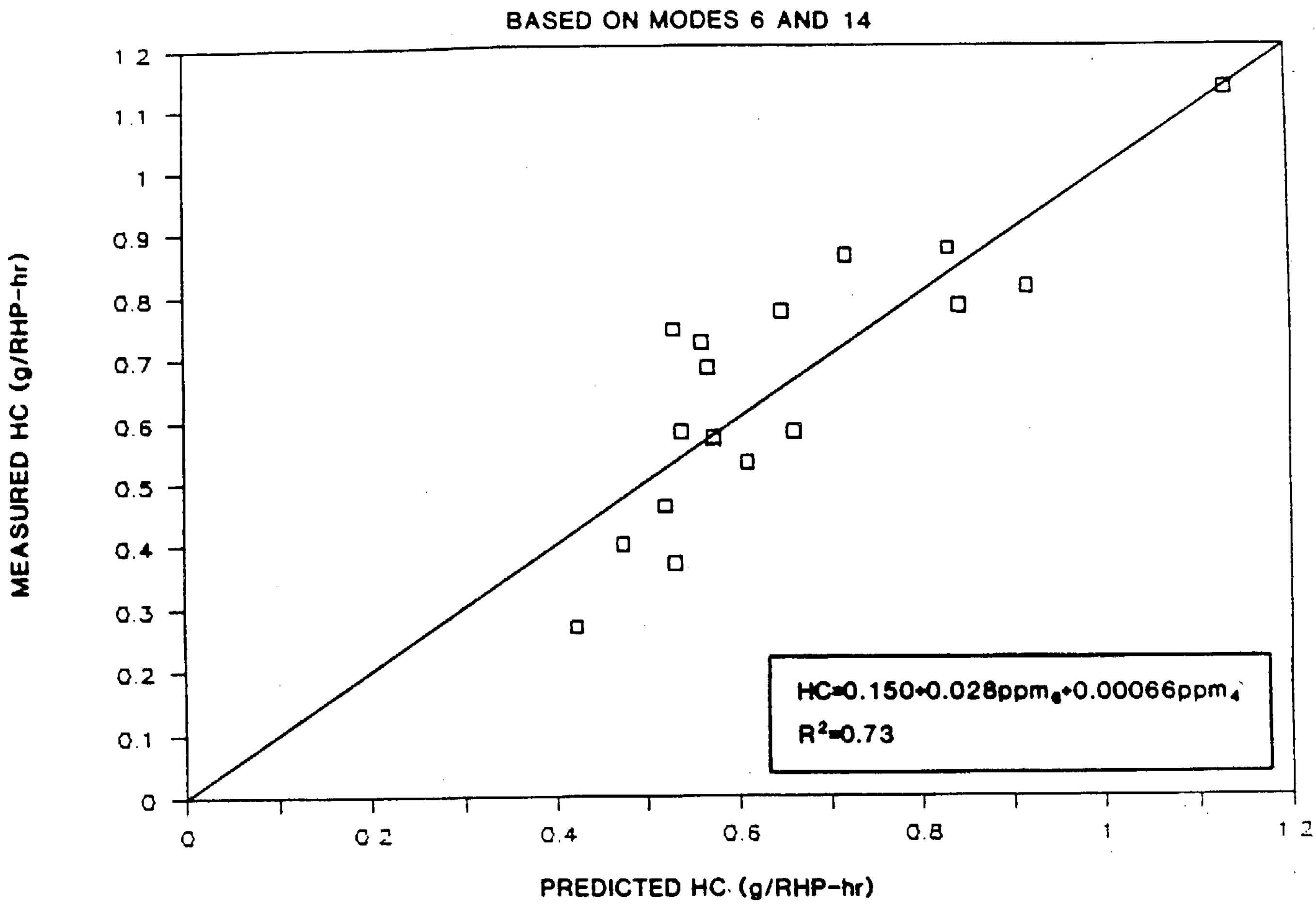

Figure 5-16. Predicted vs. Actual HC (Based on Modes 6 & 14)

6.0 ANALYSIS OF THE NEW YORK CITY EMISSIONS DATABASE

In order to obtain additional insight into the relationships between regulated emissions and smoke opacity in different operating modes, Radian obtained, keypunched, and analyzed the results of a large number of diesel vehicle emissions tests conducted at the Frost Street emissions laboratory of the New York City Department of Environmental Protection (NYCDEP). NYCDEP provided data for 315 emissions tests on 133 diesel buses, and another 118 tests on 20 heavy-duty diesel trucks. The data for each test included gaseous and particulate emissions in grams per mile and fuel consumption data in miles per gallon, measured over one or more of three transient operating cycles on a chassis dynamometer. Most of these tests include transient and steady-state smoke opacity data as well.

To our knowledge, this is by far the largest collection of in-use diesel emissions data ever collected. That it includes both smoke and transient particulate emissions data makes it especially well suited to the purposes of this study. The remainder of this section describes the procedures used in making these tests, and presents the our statistical analysis of the results.

6.1 Test Procedures and Data

Test classifications--The major emphasis of the NYCDEP program was on testing trucks and buses in use. Nearly all of the vehicles tested in the program were tested in "as-received" condition. For analytical purposes, these were classified as "baseline" tests. Many of the buses, and a few trucks, were then repaired to correct any emissions-related problems present. Depending on the extent of these repairs, the vehicle might be retested only in the "repaired" condition, or it might receive one or more "intermediate" tests before being released.

The NYCDEP test program also included a number of investigations of the effects of different maintenance items and operating variables, and of different test procedures. Several sets of back-to-back tests compared results with a dirty air filter to those with a clean one, for instance. Other test series examined the effects of plugged and/or leaking fuel injectors, proper setting of the smoke puff limiter, use of No. 1 diesel fuel and/or special fuel additives, trap-oxidizers, and use of the bus air-conditioner. The tests using dirty air filters, leaking injectors, etc. were considered representative of conditions that might be found in the field, and were thus classed with the "intermediate" tests. Tests run with trap-oxidizers, No. 1 fuel, or additives were considered unrepresentative of buses on the road, so they were given a fourth classification as "special" tests, and excluded from most of the statistical analysis.

Test procedure--The NYCDEP test program used three different transient test cycles for diesel vehicles--one cycle for trucks, and two for buses. The truck cycle used was the New York Truck Non-Freeway cycle developed under contract to EPA, as part of the CAPE-21 study which led to the Heavy-Duty Transient Cycle. One of the two bus cycles, the New York Bus Composite Cycle, was also developed as part of the CAPE-21 study. Both of these cycles represent a mix of stop-and-go and freeway driving patterns. The other bus cycle, referred to as the New York Bus 2 cycle, was developed by NYCDEP, and simulates bus operation in a densely congested urban area such as Manhattan. Figures 6-1 through 6-3 show the speed-time traces for these three cycles.

The emissions testing setup used closely resembled that for emissions testing of light-duty diesel vehicles in the Federal Test Procedure. It consisted of a heavy-duty chassis dynamometer, a constant volume sampling (CVS) system, and a dilution tunnel and filter for particulate emissions measurements. The dynamometer frictional power was set to simulate effects of air friction and rolling resistance on the vehicle, and flywheels were engaged to simulate the effects of the vehicle's inertia. The vehicle was then

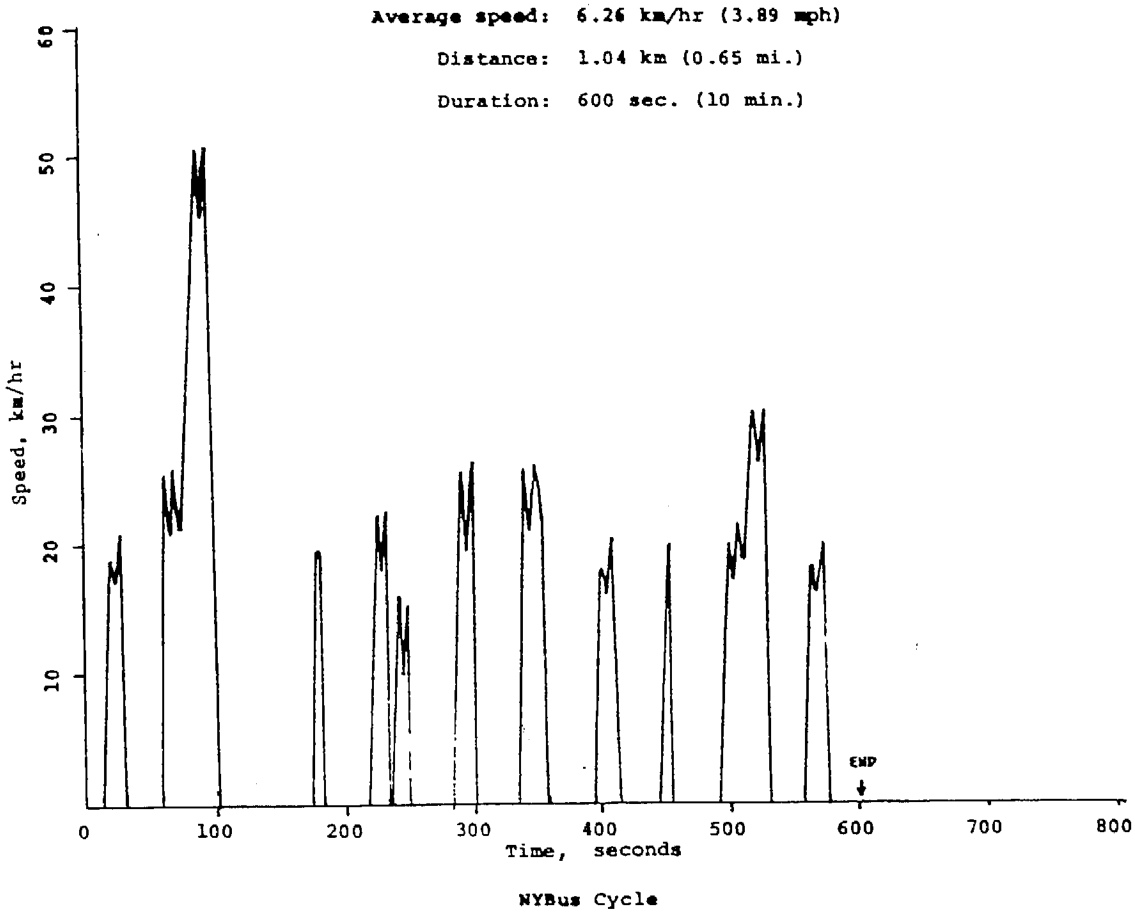

Figure 6-1. Speed vs. Time Trace for the New York Bus 2 Emissions Test Cycle

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CORPORATION

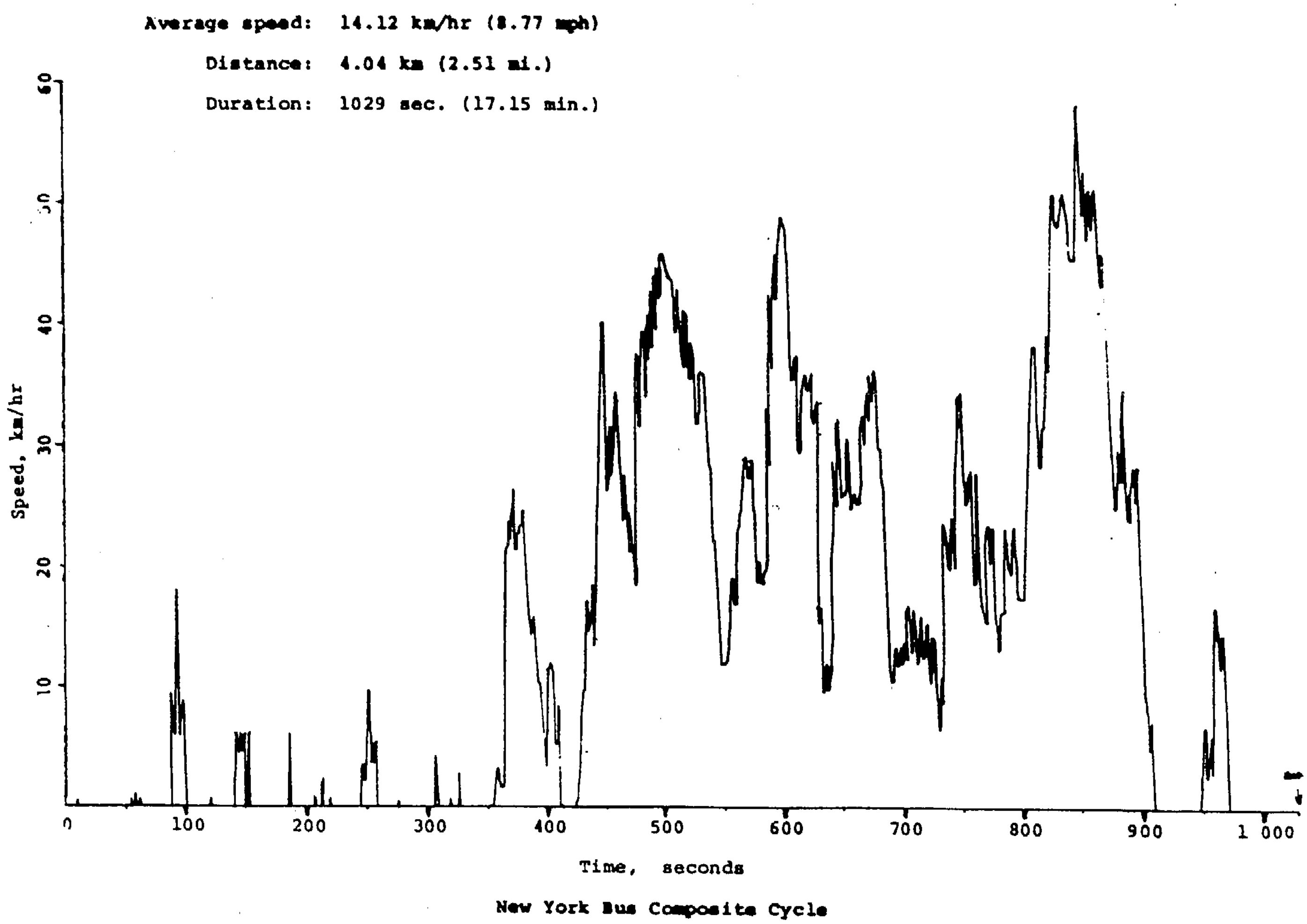

Figure 6-2. Speed vs Time Trace for the New York Bus Composite Emissions Test Cycle

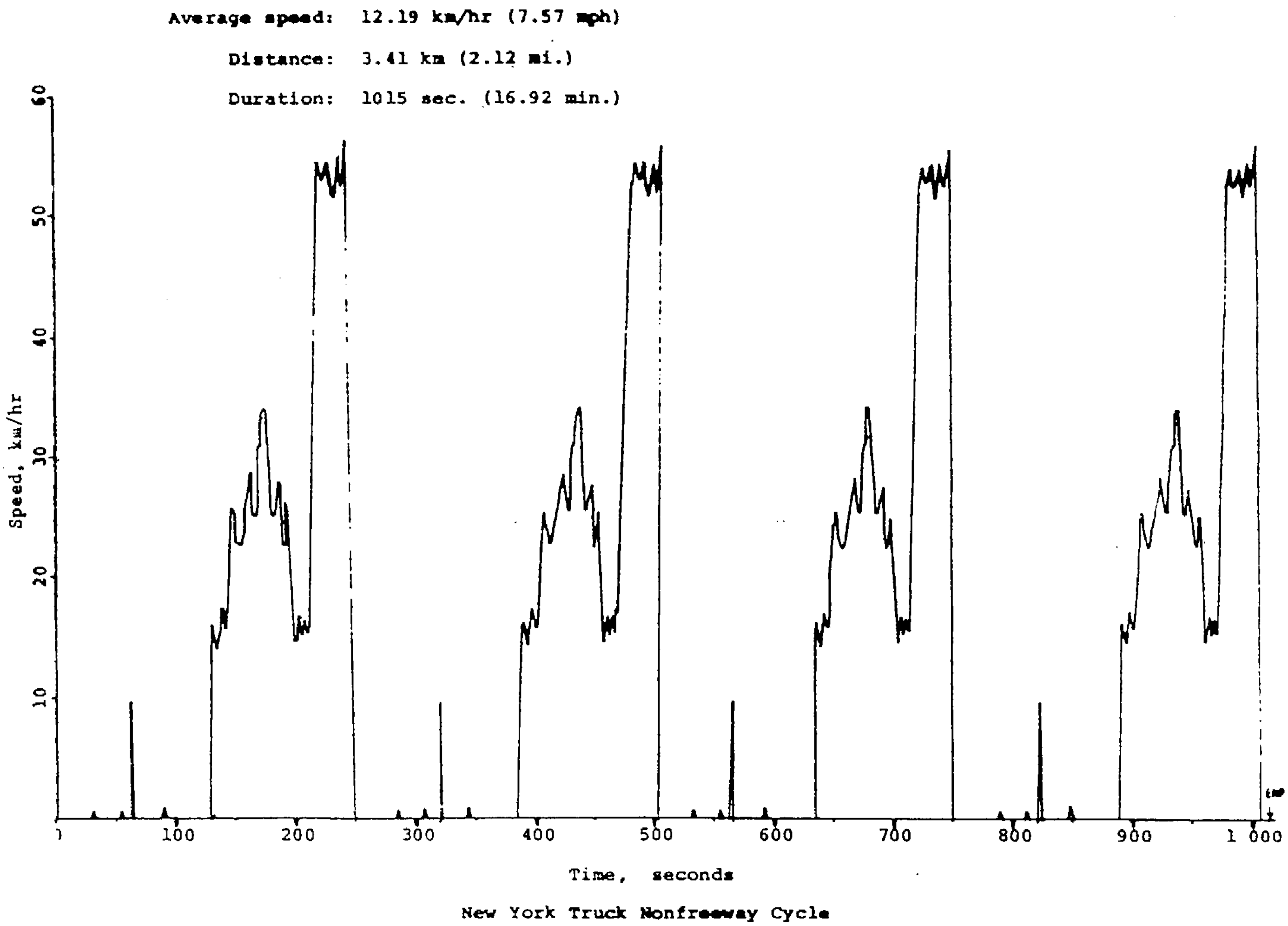

Figure 6-3. Speed vs. Time Trace for the New York Truck Nonfreeway Cycle

operated over the given driving cycle, while collecting bag samples of the gaseous pollutants. The major changes from the light-duty procedure included the use of a larger set of flywheels (capable of simulating vehicle inertia up to 19,500 lb), and a greater pumping rate due to the higher exhaust flow rates. A smaller flywheel system (capable of simulating up to 10,500 lb) was used for some of the earlier tests.

Although the flywheels used for heavy-duty testing were larger than those typical of light-duty test installations, they were still insufficient to simulate a fully-loaded bus or truck. Typical loaded weight of an urban bus is in the range of 25,000 to 30,000 lb, while the GVW ratings of the trucks tested ranged up to 50,000 lb. Since emissions tend to increase with increasing vehicle inertia, the data from these tests probably underestimate the actual emissions in use. Statistical analysis of the differences between the earlier tests at 10,500 lb and the later tests taken at 19,500 lb shows the differences in particulate and HC emissions to be fairly small, however.

The NYCDEP test program also included smoke opacity measurements in a number of operating modes. For buses, these included measurements at 30 MPH cruise, and wide-open-throttle with the transmission in neutral and drive. The 30 MPH cruise mode should be comparable to the road-load test included in the PIMT procedure developed for this project; while the WOT neutral and drive modes are directly comparable to the stabilized values in our stall idle and snap idle tests.

The NYCDEP measurements also included smoke opacity during full-power acceleration. For buses, this measurement differed from the acceleration smoke opacity measured in the PIMT in that it disregarded the initial sharp peak due to a maladjusted throttle delay (if that was present). It is thus not strictly comparable to either the peak or the stabilized values measured in the PIMT, but would be reasonably comparable to a time-averaged acceleration opacity value. For trucks, a high and low acceleration opacity value were recorded. The high value is comparable to the peak opacity value recorded in our acceleration tests.

Vehicles tested--Except for two or three vehicles, all of the buses tested in the NYCDEP program were from the City's transit fleets. Most were in-use vehicles which had been selected at random by the Transit Authority. Some tests were also run on new buses from different makers, and on newly rebuilt and refurbished vehicles. Some special tests were also run on new-technology buses, such as the new DDECS-equipped bus engines from General Motors. Except for some of the new-technology buses (which were coded as "special" tests) these buses were probably fairly representative of the publicly-owned bus fleets in use in New York. (A visual observation study conducted by NYCDEP (1984) indicates that privately-owned bus fleets in New York City are substantially smokier than the publicly-owned fleets).

Nearly all of the buses tested were equipped with one of two DDA engine models: the 6V71N or the 6V92TA. Conclusions based on these data are thus strictly applicable only to these or similar DDA bus engines. Extrapolation to other engines in other types of vehicles may not be valid, due to the possible differences in engine design and application.

The trucks tested were primarily garbage trucks from the City's sanitation fleet which had been selected by the Sanitation Department for a special test program involving fuel additives. A sprinkling of other city-owned trucks were also tested. A variety of two and four-stroke engines were included in the test fleet. The engines tested were thus probably reasonably representative of the overall medium-heavy duty fleet. Both the average smoke opacity and the range of opacities for these trucks were considerably lower than those observed in our field screening and in the visual smoke survey. This may indicate an effective fleet maintenance program, or may possibly be due to selecting only non-smoky trucks for inclusion in the test program. Since the purpose of the program was to evaluate a fuel additive, rather than to gather emissions data *per se*, this is not an unreasonable supposition.

6.2 Statistical Analysis

The emissions data provided by NYCDEP were entered into a Lotus (tm) spreadsheet, then transferred to Statistical Analysis System (SAS) databases for analysis. Table 6-1 provides the key summary statistics for the truck and bus databases. Included are the mean, median, standard deviation, and range of each of the emissions measurements, plus fuel economy, on each of the two bus test cycles and the single truck cycle. Separate compilations are given for each test classification (other than "special").

The baseline data in Table 6-1 illustrate the tremendous range of heavy-duty diesel emissions in use. Acceleration smoke opacities range from 0.5% to 57%, cruise opacities from 0.5% to 43%, particulate emissions from 1.28 to 36.7 g/mi, and NO_x emissions from 25 to 125 g/mi, even on the same test cycle. As the percentile data show, however, the distribution of emissions is highly skewed, with most vehicles concentrated in the low-to-moderate emissions range, but with a few very high emitters.

The highest HC and particulate emission rates measured were for the "intermediate" bus tests in the New York Bus 2 Cycle. These values are substantially higher than the maxima for the "baseline" tests taken before any repairs were made. This is because the "intermediate" classification includes a number of tests in which the bus was fitted with one or more leaky fuel injectors in order to determine the effect on its emissions. These effects were drastic--particulate emissions in some of these tests exceeded 30 grams/-mile, or roughly ten times the normal level. (For comparison, the highest particulate emissions measured in a "baseline" test were 16.9 g/mi. Nonetheless, the cruise-mode smoke opacities measured in leaky-injector tests were comparable to some of the road-load opacity values observed in our visual smoke survey. This indicates that similar emissions levels are not unknown in trucks in use.

TABLE 6-1. SUMMARY STATISTICS FOR THE NYCDEP DIESEL EMISSIONS DATABASE

	N	Mean	Std. Dev.	Percentiles 0th	10th	25th	50th	75th	90th	100th
BUSES										
Smoke Opacity										
Baseline										
Accel (%)	168	6.77	6.64	0.50	1.50	3.00	5.00	8.00	13.00	57.00
Cruise (%)	168	0.79	1.18	0.50	0.50	0.50	0.50	0.50	1.00	11.00
WOT-N (%)	167	3.35	8.65	0.50	0.50	1.00	1.50	3.00	5.00	100.00
WOT-D (%)	168	6.75	6.64	0.50	1.50	2.50	4.75	8.00	15.00	46.00
Repaired										
Accel (%)	25	6.38	7.05	1.00	1.50	2.00	5.00	7.00	13.50	34.50
Cruise (%)	25	0.92	1.90	0.50	0.50	0.50	0.50	0.50	0.50	10.00
WOT-N (%)	25	2.42	5.30	0.50	0.50	0.50	1.00	2.00	3.00	27.50
WOT-D (%)	25	7.46	8.82	0.50	1.00	2.50	4.50	7.00	17.00	33.00
Intermediate										
Accel (%)	62	24.37	27.83	1.00	3.00	5.50	9.25	46.00	72.50	87.50
Cruise (%)	62	7.96	13.38	0.50	0.50	0.50	0.50	11.00	33.50	42.50
WOT-N (%)	62	10.23	13.59	0.50	0.50	1.00	2.00	27.00	32.50	44.00
WOT-D (%)	62	22.95	25.35	1.00	2.50	5.00	9.00	38.00	69.00	70.00
Emissions: NY Bus 2 Cycle										
Baseline										
HC g/mi	122	8.35	3.48	4.16	5.60	6.38	7.83	9.15	11.19	29.52
NOx g/mi	122	55.82	20.28	25.22	34.64	40.74	52.01	67.52	79.61	124.77
PM g/mi	105	4.26	3.22	1.28	1.74	2.22	3.42	4.72	7.33	16.89
MPG	122	2.93	0.52	1.90	2.28	2.55	2.85	3.28	3.55	4.44
Repaired										
HC g/mi	24	9.76	4.82	5.14	6.11	7.03	8.45	11.82	12.92	29.18
NOx g/mi	24	59.42	21.11	30.24	35.14	42.77	56.12	67.36	82.24	120.80
PM g/mi	18	3.61	2.27	1.50	1.70	2.13	3.00	4.12	6.70	10.67
MPG	24	3.24	0.58	2.20	2.53	2.84	3.25	3.54	3.89	4.80
Intermediate										
HC g/mi	66	17.86	14.11	6.48	7.42	8.15	11.75	28.42	44.01	48.03
NOx g/mi	66	47.71	13.17	29.75	33.40	37.70	46.86	52.34	61.41	94.63
PM g/mi	53	11.49	11.08	1.16	3.10	4.11	5.76	12.92	31.70	36.70
MPG	66	3.31	0.35	2.40	2.86	3.11	3.30	3.46	3.80	4.20

(Continued)

TABLE 6-1. SUMMARY STATISTICS FOR THE NYCDEP DIESEL EMISSIONS DATABASE (Continued)

	N	Mean	Std. Dev.	Percentiles 0th	10th	25th	50th	75th	90th	100th
Emissions: NYB Composite										
Baseline										
HC g/mi	88	4.43	1.19	2.37	3.27	3.73	4.21	4.80	5.68	8.71
NOx g/mi	88	33.45	9.97	16.18	22.37	25.39	31.80	40.23	46.74	61.20
PM g/mi	38	2.21	2.23	0.76	0.90	1.08	1.43	2.16	3.78	10.53
MPG	88	4.99	0.77	3.40	4.02	4.42	5.00	5.40	6.00	7.70
Repaired										
HC g/mi	39	4.57	1.06	3.69	3.69	3.76	3.88	5.12	6.65	6.65
NOx g/mi	9	40.82	11.98	24.51	24.51	32.96	38.98	45.86	63.60	63.60
PM g/mi	7	1.33	0.47	0.79	0.79	0.82	1.46	1.76	1.97	1.97
MPG	9	4.78	0.49	4.15	4.15	4.34	4.80	5.17	5.40	5.40
Intermediate										
HC g/mi	4	4.82	1.55	3.36	3.36	3.52	4.69	6.13	6.56	6.56
NOx g/mi	4	42.07	5.74	33.72	33.72	38.32	44.14	45.82	46.28	46.28
PM g/mi	4	0.98	0.25	0.60	0.60	0.85	1.11	1.11	1.11	1.11
MPG	4	5.05	0.39	4.58	4.58	4.75	5.10	5.37	5.46	5.46
TRUCKS										
Smoke Opacity										
Baseline										
Accel Max (%)	56	14.98	8.29	6.00	7.00	10.00	12.00	20.00	22.00	50.00
Accel Min (%)	56	8.29	3.75	4.00	5.00	5.00	7.00	10.00	12.00	20.00
Cruise (%)	56	1.35	1.62	0.50	0.50	0.50	0.50	1.00	4.00	8.00
Emissions										
Baseline										
HC g/mi	72	4.54	2.39	1.98	2.74	3.05	3.49	5.53	7.81	15.18
NOx g/mi	72	37.25	11.62	19.40	25.62	30.93	36.06	40.00	50.50	81.64
PM g/mi	61	2.46	0.77	1.28	1.86	2.02	2.36	2.67	3.08	6.92
MPG	72	4.40	0.91	2.75	3.40	3.94	4.23	4.66	5.40	7.70

Smoke opacity vs. particulate emissions--An important area of uncertainty in the development of the proposed I/M test procedures was the strength of the correlation between smoke opacity measurements in specific operating modes and in-use particulate emissions. The emissions test data discussed in Sections Four and Five provided some indication of this relationships, but the limited sample size and concerns over the representativeness of the steady-state test cycle would have limited our confidence in the conclusions. The much larger size of the NYCDEP database, together with the more representative test cycles used, allowed us to draw conclusions with much greater confidence.

Our statistical analysis of the emissions test data showed strong correlations (significant at at least the 99% level) between each of the smoke opacity tests and particulate emissions in each test cycle. A strong correlation between smoke and HC emissions was also noted on the NY Bus 2 cycle. Weaker--but still significant--correlations between some smoke modes and HC emissions on the Bus Composite and Truck cycles were also noted. The correlation coefficients and significance levels are shown in Table 6-2.

A number of single and multi-variable models relating smoke to particulate emissions were evaluated. The best-fit parameters and regression statistics for the final models are shown in Table 6-3. For the New York Bus 2 cycle, the single-variable model with the best explanatory power was the one incorporating acceleration smoke opacity, while for the Bus Composite and Truck cycle data, models based on acceleration and cruise smoke opacities were nearly equal in explanatory power. Figures 6-4 through 6-8 plot the observed particulate data vs. smoke opacity in the different modes, showing the best-fit lines for the one-variable models.

For the Bus Composite and Truck datasets, a two-variable model incorporating both acceleration and cruise opacities was found to provide significantly greater explanatory power than either variable used alone. Interestingly, substitution of the high idle (wide-open throttle in neutral)

TABLE 6-2. CORRELATION BETWEEN EMISSIONS AND SMOKE OPACITY

	Smoke Opacity In			
BUSES	Acceleration	Cruise	WOT-N	WOT-D
New York Bus 2				
PM				
R^2	0.945	0.881	0.839	0.939
Signif.*	<0.0001	<0.0001	<0.0001	<0.0001
HC				
R^2	0.938	0.933	0.884	0.926
Signif.	<0.0001	<0.0001	<0.0001	<0.0001
New York Bus Composite				
PM				
R^2	0.759	0.763	0.802	0.467
Signif.	<0.0001	<0.0001	<0.0001	<0.0014
HC				
R^2	0.224	0.524	0.132	0.226
Signif.	0.032	0.001	0.213	0.030

	Smoke Opacity In		
TRUCKS	Accel (Peak)	Accel (Min)	Cruise
PM			
R^2	0.746	0.669	0.769
Signif.	<0.0001	<0.0001	<0.0001
HC			
R^2	0.101	0.182	0.020
Signif.	0.46	0.18	0.88

* Probability of showing this degree of correlation by random chance.

TABLE 6-3. LINEAR REGRESSION OF SMOKE OPACITY VS. PARTICULATE EMISSIONS

		R^2
One Variable Models		
NY Bus 2	$PM = 1.78 + 0.417\ O_{acc}$	0.89
NY Bus Composite	$PM = 0.65 + 0.227\ O_{acc}$	0.58
NY Bus Composite	$PM = 0.98 + 0.958\ O_{crs}$	0.58
NY Truck	$PM = 1.42 + 0.070\ O_{acc}$	0.55
NY Truck	$PM = 1.97 + 0.371\ O_{crs}$	0.59
Two Variable Models		
NY Bus 2	$PM = 1.84 + 0.402\ O_{acc} + 0.036\ O_{crs}$	0.89
NY Bus 2	$PM = 1.78 + 0.359\ O_{acc} + 0.134\ O_{wotn}$	0.90
NY Bus Composite	$PM = 0.64 + 0.137\ O_{acc} + 0.590\ O_{crs}$	0.71
NY Bus Composite	$PM = 0.62 + 0.130\ O_{acc} + 0.264\ O_{wotn}$	0.76
NY Truck	$PM = 1.63 + 0.036\ O_{acc} + 0.231\ O_{crs}$	0.65

Variable Definitions

PM = Particulate emissions (g/m)

O_{acc} = Acceleration smoke opacity (%)

O_{crs} = Cruise smoke opacity (%)

O_{wotn} = Wide-open throttle (neutral) smoke opacity (%)

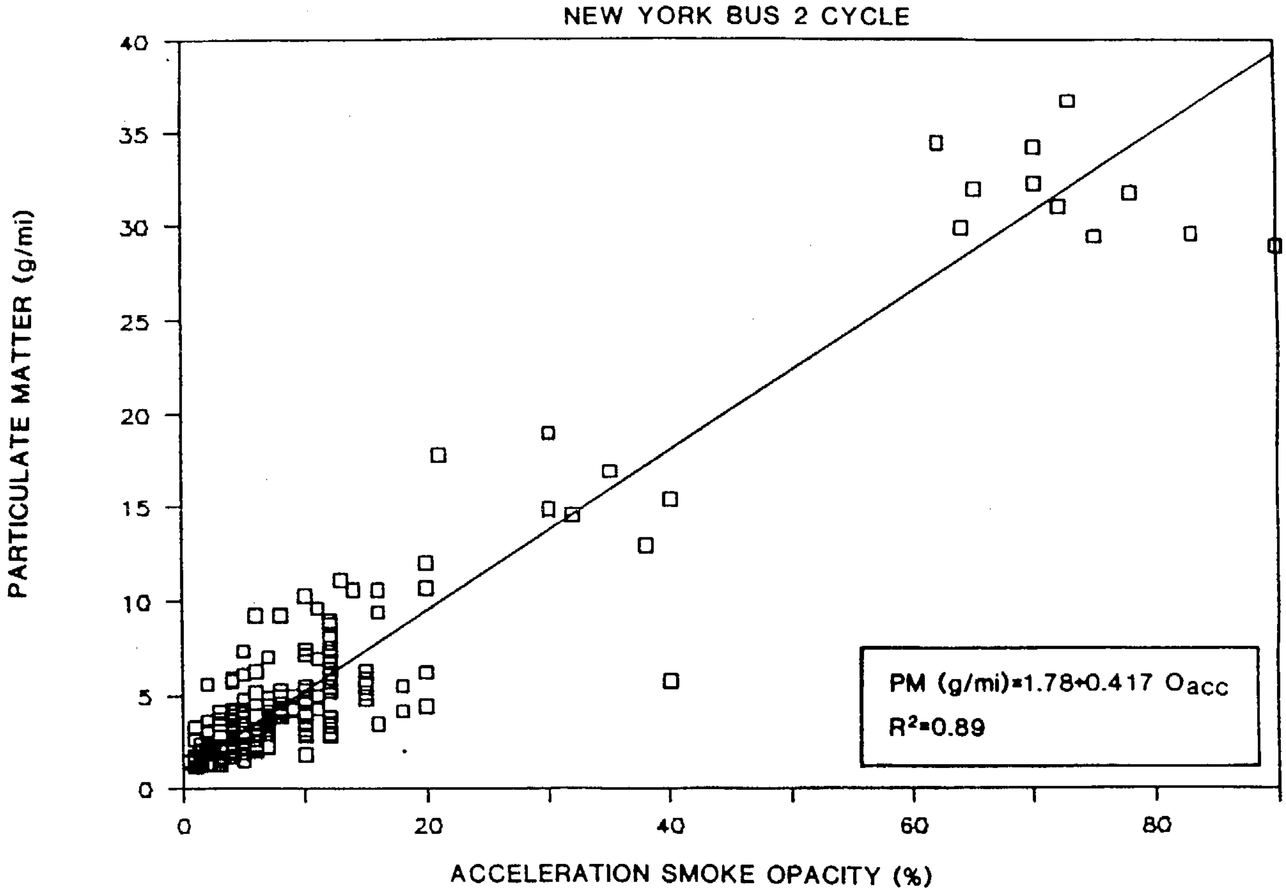

Figure 6-4. Acceleration Smoke Opacity vs. Particulate Emissions (New York Bus 2 Cycle)

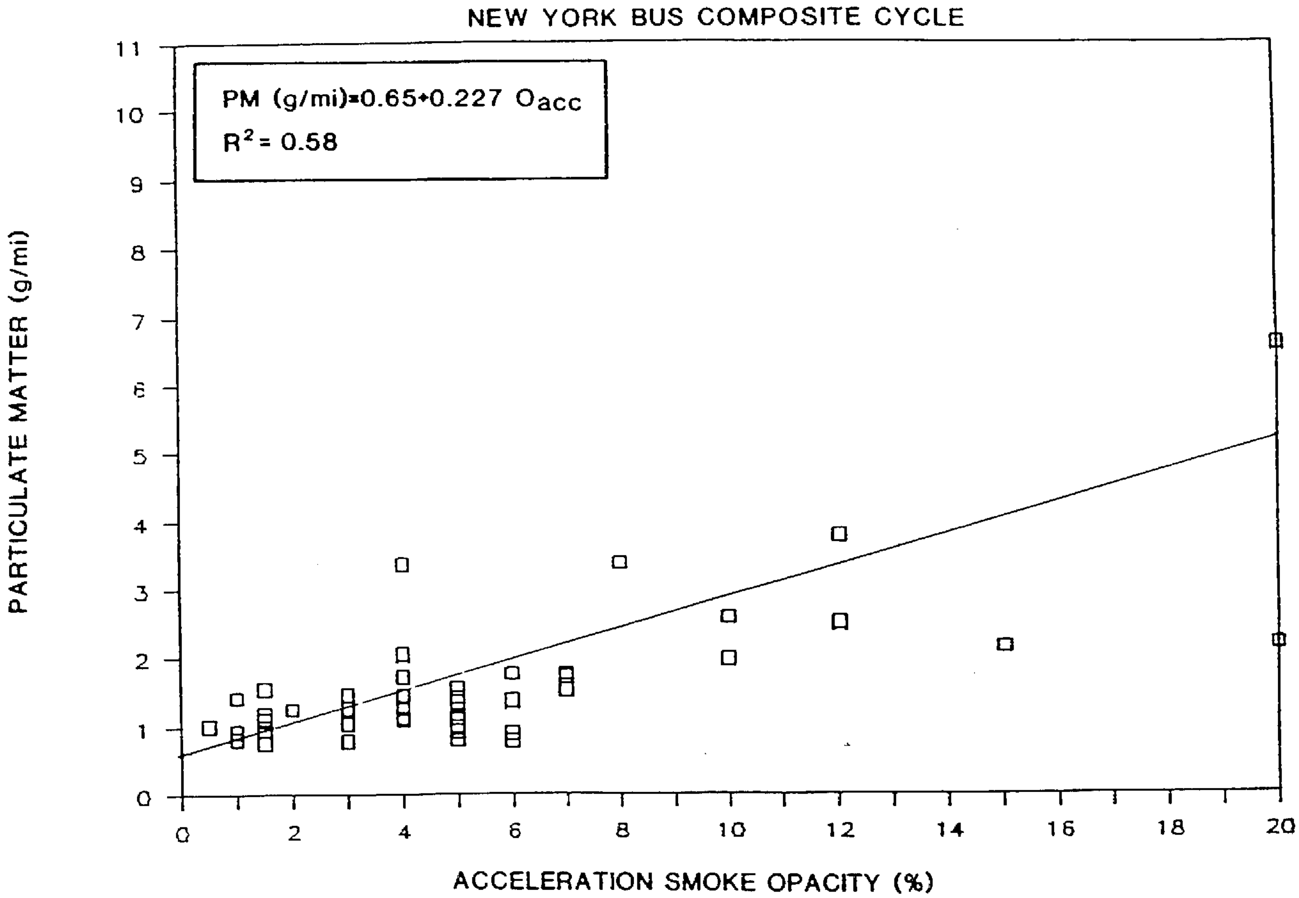

Figure 6-5. Acceleration Smoke Opacity vs. Particulate Emissions (New York Bus Composite Cycle)

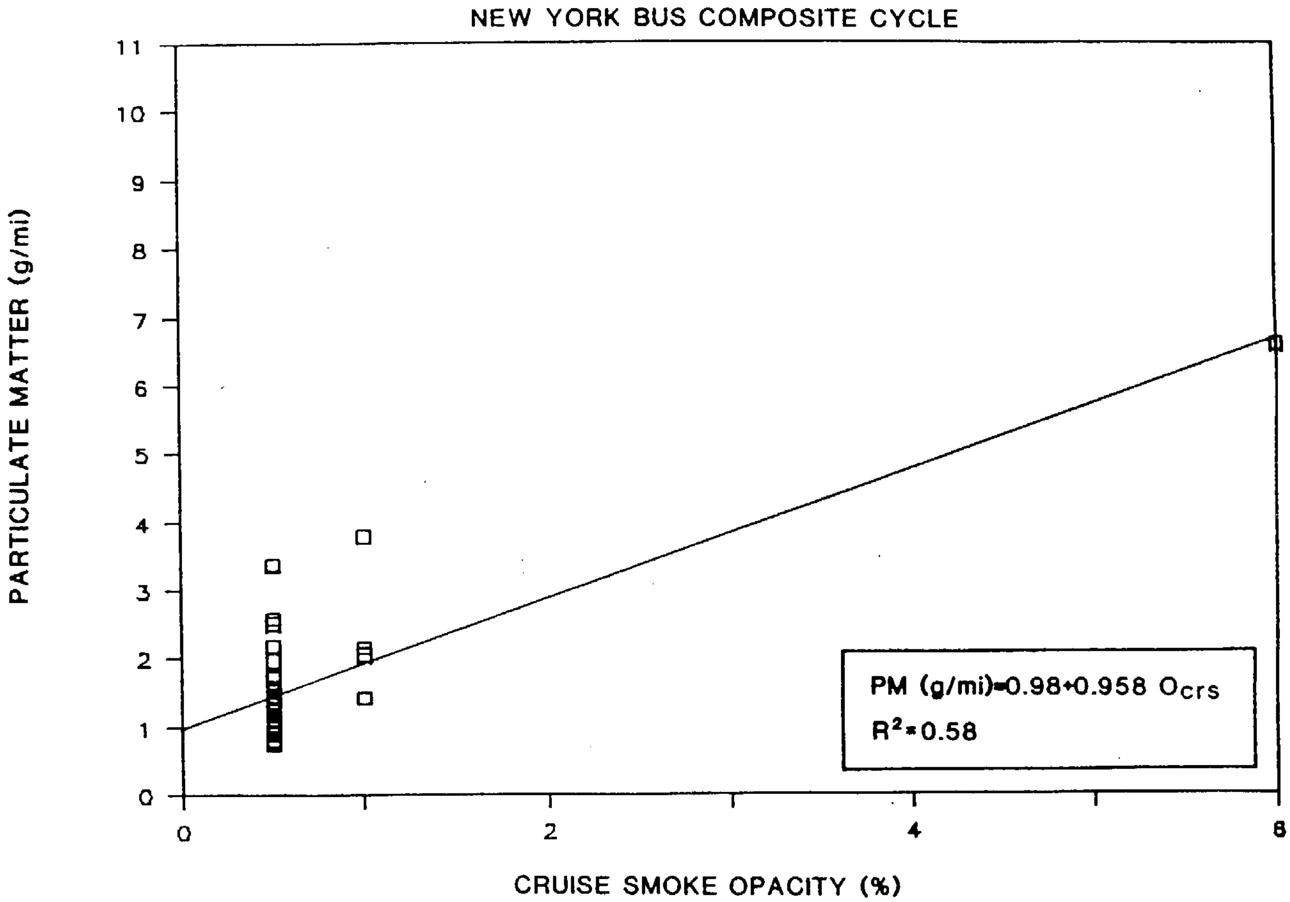

Figure 6-6. Cruise Mode Smoke Opacity vs. Particulate Emissions (New York Bus Composite Cycle)

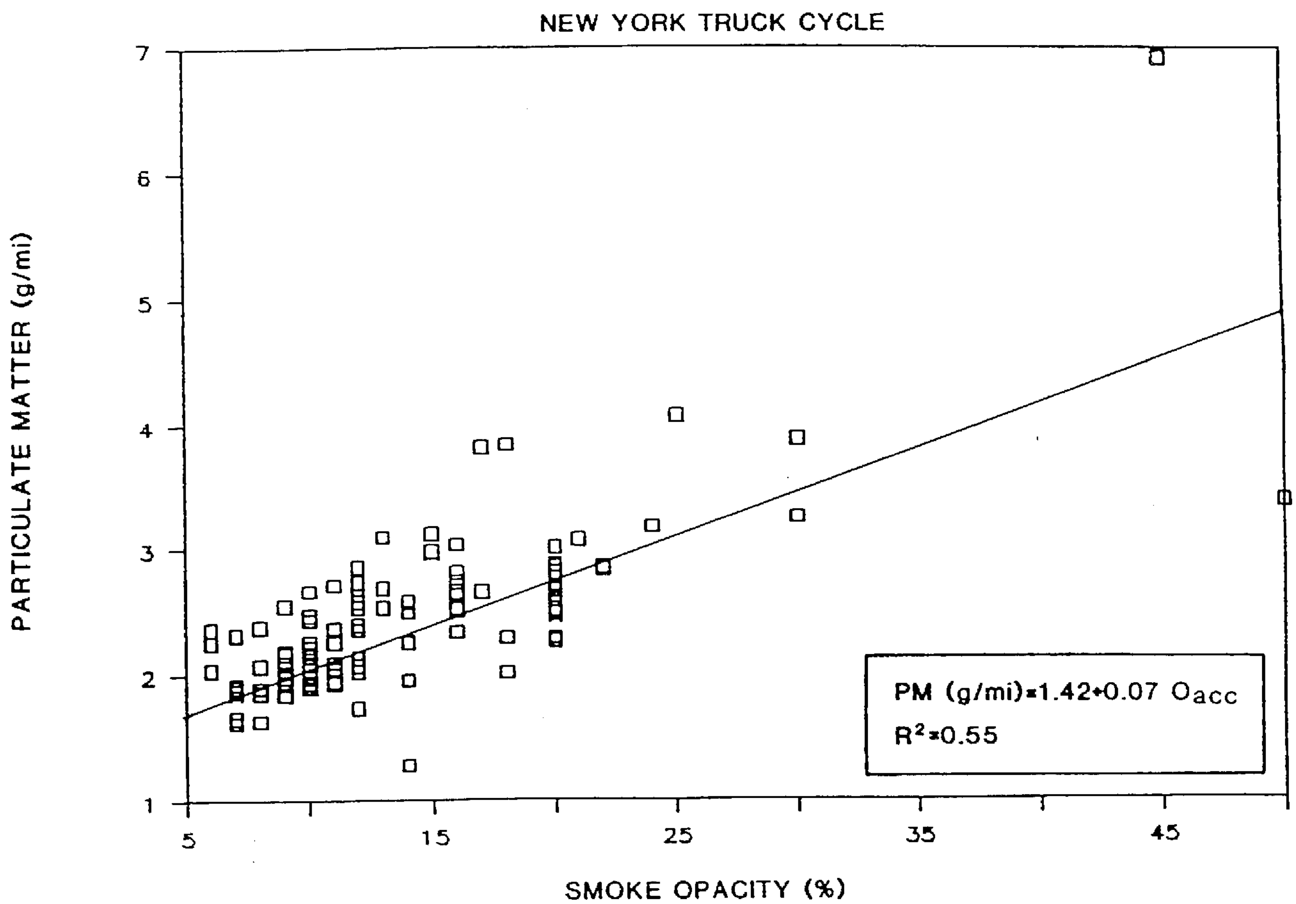

Figure 6-7. Acceleration Smoke Opacity vs. Particulate Emissions (New York Truck Cycle)

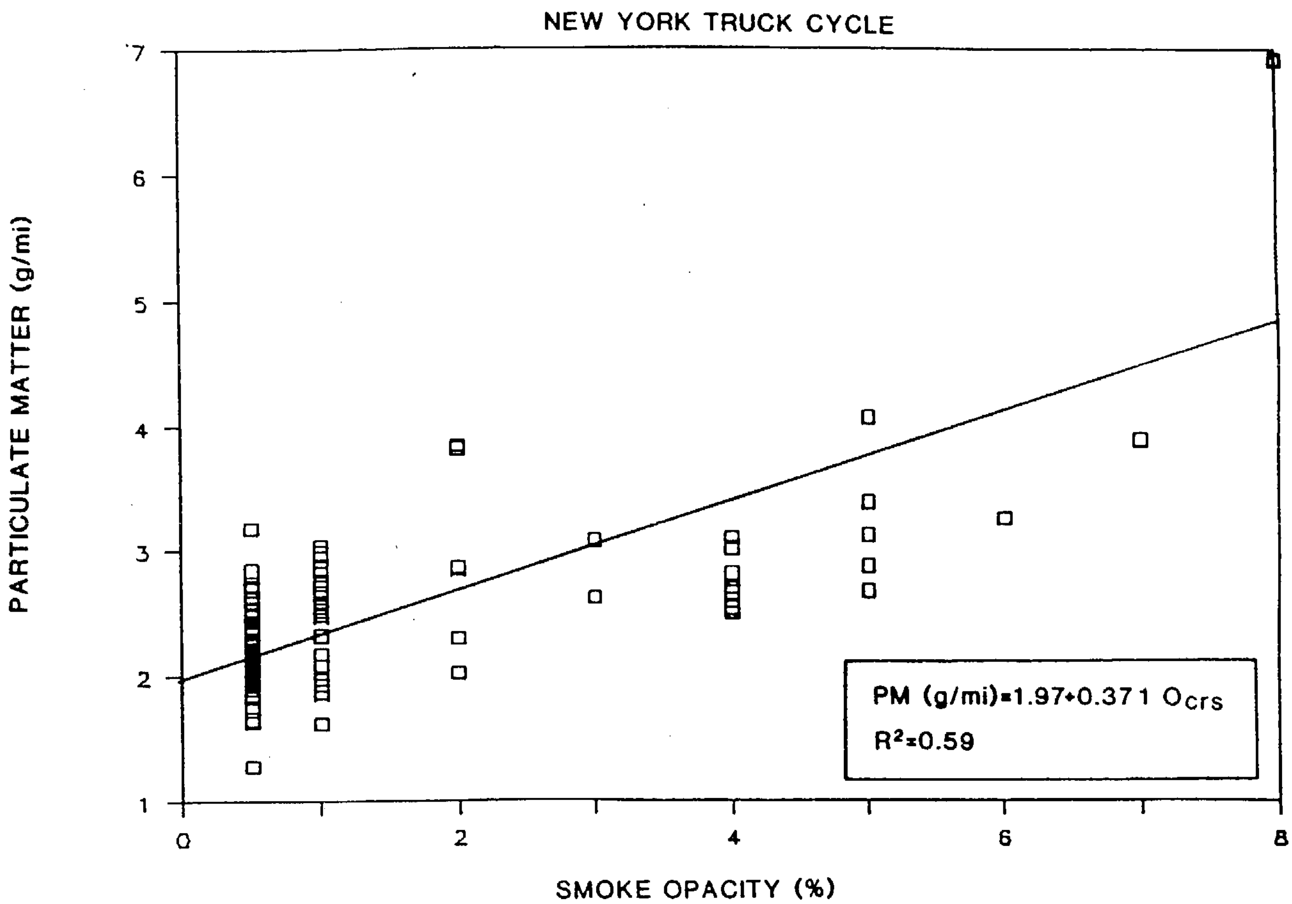

Figure 6-8. Cruise Mode Smoke Opacity vs. Particulate Emissions (New York Truck Cycle)

smoke opacity for the cruise opacity gave an even better fit to the Bus Composite data. No high-idle opacity data were available for the trucks, so it is unknown whether this would have been the case for them as well.

The correlation coefficients in Tables 6-3 and 6-4 indicate a strong correlation between smoke opacity and particulate emissions on the New York Bus 2 Cycle, while the correlation for the other two cycles is significantly weaker. Some of this difference is certainly due to the differences in cycle characteristics, as indicated by the improved explanatory value of the two-variable models for the Bus Composite Cycle and Truck Cycle data. Since the NY Bus 2 cycle consists mostly of sharp accelerations, a strong correlation with the acceleration mode data would be expected. The other two cycles include a significant amount of operation in cruise mode as well as accelerations. It is not surprising, then, that the addition of cruise mode opacity to the model should improve the correlation.

Another reason for the stronger correlation in the New York Bus 2 cycle can be seen by comparing Figures 6-4, 6-5, and 6-7. As these plots show, the range of smoke opacities and particulate emissions observed in the Truck Cycle and the Bus Composite Cycle is fairly small compared to that in the New York Bus 2 Cycle. As noted above, both the average smoke opacity and range of opacities in the truck test fleet were significantly lower than those we observed in the ROC screening tests and in the visual smoke survey. The subset of buses tested on the New York Composite cycle had a similarly restricted range of smoke opacities. To obtain a strong correlation requires that the independent variables in the dataset exhibit a sufficiently broad range--otherwise, the effects of other perturbing influences can mask the underlying interactions.

In addition to the linear regression analyses, a pass/fail analysis was performed using the failure criteria developed in Section Two. The effects of two I/M tests were simulated: acceleration opacity and road-load opacity. Buses were classed as passing or failing an I/M test based on their

TABLE 6-4. PASS/FAIL ANALYSIS FOR TWO SETS OF I/M FAILURE CRITERIA: NEW YORK BUS DATABASE

Original Failure Criteria

$O_{acc} > 35\%$ or $O_{crs} > 6\%$

	No. of Veh.	Percent of Veh.	Mean Emissions (NYC Bus 2) PM	Mean Emissions (NYC Bus 2) HC
True Negative	147	69.3	3.08	7.90
False Negative (Error of omission)	44	20.8	8.21	10.98
False Positive (Error of commission)	0	0.0	--	--
True Positive	21	9.9	26.67	37.53
Total	212	100.0		
Percent Excess Emissions Detected			68.5%	80.8%

Revised Failure Criteria

$O_{acc} > 15\%$ or $O_{crs} > 3\%$

	No. of Veh.	Percent of Veh.	Mean Emissions (NYC Bus 2) PM	Mean Emissions (NYC Bus 2) HC
True Negative	139	65.6	3.04	7.89
False Negative (Error of omission)	34	16.0	7.17	10.71
False Positive (Error of commission)	8	3.8	4.28	7.96
True Positive	31	14.6	20.71	29.26
Total	212	100.0		
Percent Excess Emissions Detected			80.9%	83.4%

opacity measurements; and as low or high emitters based on their emissions on the New York Bus 2 cycle. The reason for using this database, rather than the Truck or Bus Composite cycles, was that it was considered more representative of the range of emissions and smoke opacity in the fleet as a whole. Vehicles exceeding 35% opacity on the acceleration mode or 6% opacity in cruise mode were classed as having failed the test; those below these levels would pass. Vehicles with either HC or particulate emissions exceeding 150% of the mean for newly-repaired vehicles were classed as "high emitters", those below this level as "low emitters". Table 6-4 shows the results of this analysis.

For the bus fleet tested, using the original failure criteria, 69.3% of the buses were low emitters, and all of these passed the I/M test (there were no false positives). The remaining 30.7 percent of the buses were classed as high emitters. Of these, more than two-thirds (20.8% of the total) also passed the I/M test, causing them to be classed as false negatives. Only 9.9% of the buses failed the I/M test. However, this small group accounted for more than 68% of the total excess particulate emissions and 80% of excess hydrocarbon emissions for the entire fleet (excess emissions were defined as those exceeding the 75th percentile level for baseline vehicles). Mean emissions from this group were 26.7 g/mi of particulate. This is nearly nine times the mean for the low-emitting group, and three times the mean for the false negative group. Thus, while these tests would not have detected all high emitters, they would have detected the highest emitters, which account for most of the excess emissions.

Most of the buses failing the I/M test failed on both modes, indicating that the two failure criteria are roughly comparable in stringency. However, several high-emitting vehicles were found which could pass either the acceleration or cruise mode tests, but which failed the other one. Thus, the combination of the two failure criteria was more effective than either one alone in identifying high emitters.

A similar analysis was carried out for the WOT-N and WOT-D smoke opacity data. The inclusion of tests based on these two criteria reduced the number of false negatives by about 50%, but produced an even larger number of false positive tests. Furthermore, the additional high-emitting vehicles identified by these tests were generally not gross emitters. An additional concern with these tests is that--unlike cruise and acceleration modes--the WOT-N and WOT-D modes do not represent typical engine operating conditions, and there is thus greater uncertainty over the extrapolation of these results from the limited set of bus engines sampled to the other engines.

Examination of the bus data, as well as the results of Shears (1986), and Sierra Research (Crawford, et al, 1985) indicated that, for buses at least, the failure criteria for smoke opacity could be made considerably more stringent than our initial proposals in Section Two. Accordingly, the above analysis was redone using failure criteria of 15% opacity in acceleration mode and 3% opacity in cruise. This reduced the percentage of false negatives from 20.8% to 16%, increasing the number of true positives by the same amount. At the same time, however, eight false positive tests (low-emitting vehicles which failed the I/M test) were also created.

All of the low-emitting buses which failed the more stringent smoke opacity standards failed the peak acceleration opacity criterion; none failed the cruise mode test. It is questionable, therefore, whether these failures should actually be classed as errors of commission. Each of these buses was actually emitting mildly offensive levels of visible smoke on acceleration, even though their total particulate levels were not excessive. The I/M tests are intended to detect both offensive smoke and excess emissions. Repairs to reduce the high smoke levels would thus not have been inappropriate.

7.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In Task Two of this project, Radian developed a number of candidate I/M test procedures for the Roadside Opacity Check (ROC) and the Periodic I/M Test (PIMT). These procedures are described in Section Two. Smoke opacity test procedures proposed for the ROC were the following: free acceleration, snap idle, stall idle, and lug-down against the service brakes. For the PIMT, the proposed test procedures included smoke opacity measurements over the lug-down curve, in simulated road-load operation at 75% power, in a simulated full-power acceleration, and a snap idle. In addition, measurements of HC and NO_x concentrations in specific operating modes were proposed.

These proposed test procedures were evaluated in vehicle testing conducted during Task Four. Fifty-two trucks were screened using the candidate ROC procedures. Based on the screening results, eleven of these trucks were selected for testing using the PIMT as well as dynamometer emissions measurements. Six trucks were then diagnosed, repaired, and retested. The results of the field screening tests are given in Section Three, and the results of the PIMT and dynamometer tests in Section Four. Section Five presents our statistical analysis of the test results.

To broaden the statistical basis for our conclusions, Radian obtained and analyzed data on the diesel emissions tests performed by the New York City Department of Environmental Protection. These data included both smoke and emissions measurements--the latter taken over one of several transient driving cycles on a chassis dynamometer. Our analysis of these data generally confirmed the results of our analysis of the data from Task Four.

Conclusions

Based on the test data and analysis presented in this report, the following conclusions and recommendations can be made.

Roadside Opacity Check

- The peak acceleration smoke opacity test appears to be the most effective of the four candidate procedures proposed for the ROC. This test also has the advantage of being applicable to either manual or automatic transmissions. However, a change in instrumentation to determine the "average" rather than the peak opacity during acceleration might give a better correlation with transient emissions. Further research on this subject is recommended.

- The stall idle test involves very similar operating conditions and produces similar results. It appears to be an acceptable alternate test for vehicles with automatic transmissions. Due to the extreme operating conditions, however, there is some risk of damage to the transmission in performing this test. While no transmissions were damaged in our testing, or in other tests reported to date, some transmission failures would be expected if such tests became widespread.

- The proposed failure criterion for peak opacity in the acceleration and stall idle tests was 35% (or 5% over the Federal Peak certification, if that is higher). This appears to be appropriate for trucks, and we recommend that it be retained. Alternatively, an opacity cutoff of 50% (equivalent to the Federal Smoke Test criterion) could be used, but this would result in a much lower failure rate, and some trucks with visually offensive smoke levels would pass. Buses are capable of meeting a more stringent failure criterion of 15% peak smoke opacity.

- Separate failure criteria were proposed for stabilized smoke opacity in the acceleration and stall idle tests. Based on the New York City database, these modes can identify some additional high emitters, but they also create a disproportionate number of errors of commission. We recommend omitting these test criteria from the final procedure.

- The snap idle test procedure is easier and requires less space to perform than the acceleration test, but the results correlate poorly with emissions--resulting in a greater number of errors of commission. Shears and coworkers (1986) also found that it did not always detect air system-related problems, which are quite common. We recommend that this test be dropped for general use, although it may still prove useful with specific makes of engines.

- The lug-down test procedure using the vehicle's service brakes is difficult to perform, shows poor repeatability, and is less effective than other procedures in identifying high emitters. We recommend that this test be dropped.

- Visual estimates of smoke opacity--even when performed by persons without formal training in opacity estimation--were found to correlate well with the values measured with the opacimeter. Since no equipment or contact with the vehicle is required, visual estimation is much faster than opacimeter measurements. We recommend that this approach be used for initial screening in ROC, with doubtful or protested cases being resolved by retesting with an opacimeter. Using this approach, it would be possible to screen essentially every truck passing through a truck weigh station or similar facility.

<u>Periodic I/M Test</u>

- Acceleration smoke opacity correlates fairly well with particulate emissions under transient operating conditions, but poorly with steady-state emissions. The acceleration peak opacity is also a good measure of offensive in-use smoke. The acceleration test showed good repeatability, and was the most effective test for identifying high hydrocarbon and particulate emitters, both in the Task Four tests and the NYCDEP data. We recommend that this test be included in the PIMT.

- The addition of smoke opacity in road-load cruise to the peak smoke opacity significantly improved the correlation between smoke measurements and particulate emissions in the NYCDEP database. This test also identified some high-emitting vehicles in the NYCDEP data base which passed the acceleration test, and it generated no errors of commission. We recommend that this test be included in the PIMT as well.

- The failure criterion proposed for the dynamometer acceleration test in the PIMT was 35% peak opacity. This criterion appears to be appropriate. For the road load cruise test, the proposed failure criterion was 5% opacity. This appears slightly lax--a cutoff of 4% opacity at 75% power and rated speed appears more appropriate.

- Peak lug-down smoke opacity correlates well with steady-state emissions, but we have no data to assess its correlation with transient results. This test identified fewer high emitters in the Task Four testing than did the acceleration test, and did not identify any high emitters that the acceleration test missed. In a larger sample, however, this might not have been true. This test is also clearly related to on-road smoke emissions in full-power operation. We recommend that this test be included in the PIMT.

- As discussed above for the ROC, the snap idle test correlates poorly with emissions, and generates more errors of commission than the acceleration test. This is apparently due to design features which make some engines more sensitive to this test than others. We recommend that this test be dropped from consideration for general use, although it may still prove useful with specific makes of engines.

- NO_x concentrations in modes 4 and 5 (50% and 75% power at rated speed) of the chassis dynamometer test correlate well with cycle composite NO_x emissions. This measurement could be used to identify vehicles with excessive NO_x emissions due to tampering or improper replacement of fuel injection pumps. We recommend that this measurement be included in the PIMT.

- The combination of HC emissions in modes 6 (full power/rated speed) and 14 (no load/governor speed) correlates well with cycle-composite HC emissions measured in the 13-mode cycle. Further research will be needed to determine whether this correlation will hold for HC emissions in transient operation, but we consider it likely that this will be the case. We recommend that this measurement also be included in the PIMT.

Repairs

- The repairs performed resulted in smaller emissions benefits than had been anticipated for several of the trucks. In two cases, this appeared to result from excessively retarded fuel injection timing in the repaired vehicle. In other cases, the problem appeared to lie with inadequate diagnosis. Further work to develop effective emissions-related diagnostic and repair procedures for heavy-duty diesels may be required.

General

- The data and analysis presented in this report demonstrate the technical feasibility of identifying heavy-duty diesel vehicles which are excessive emitters, by means of simple tests based on smoke opacity and NO_x and HC concentrations.

- Further work with a larger truck sample is needed to refine the failure criteria, to improve estimates of the failure rates and emissions reductions from repaired vehicles, and to better define the relationships between smoke opacity and in-use particulate and HC emissions. To reflect actual operating conditions, this work should be conducted using a transient-capable chassis dynamometer. As a possible alternative, techniques for mass emissions measurements on vehicles in normal on-road use might be developed.

  In this further testing, steps should be taken to obtain a random sample of trucks in use, rather than relying on volunteer fleets. The volunteer (primarily publicly-owned) fleets in our test program exhibited much lower smoke than observed in the visual smoke survey. This probably reflects significantly better maintenance than the average. A realistic assessment of in-use emissions must include the occasional "gross" emitter, which is unlikely to be found in a well-maintained fleet.

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